AutoStar CCD Photometry

A Step-By-Step Guide

by

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Modified DSI™ Pro CCD Camera with BVRI Photometric filters
On Meade 12-inch LX200 GPS Telescope

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Preface

There are at least two avenues to CCD photometry. First is for someone who knows precisely what they want and digs into learning how to achieve their goal. If they have previous experience with single-channel photometry, the learning curve is much easier. Another avenue to CCD photometry is for the astronomer who starts with visual observing, moves to astrophotography and then to CCD imaging. After taking many "pretty pictures" this person decides there must be something more that can be done with the equipment. Since the basis of CCD photometry requires images being taken, this person has a "jump-start" on learning CCD photometry. There is still a great deal to learn in order to produce usable photometric data from the images, however.

Many people are under the impression that a very expensive CCD camera is needed. Certainly some of the upper-end CCD cameras designed specifically for CCD photometry are excellent for the purpose; however, the cost can be well out of sight for most astronomers. Many people think you need a high-altitude, dark-sky location to do useful photometry. This is not true. Unlike imaging of faint deep-sky objects, most CCD photometry can be done within an urban, light-polluted area. While it is true the darker the location the fainter the stars you will be able to image, there are many lifetimes' worth of brighter objects just begging to be observed.

Having worked with single-channel photometry for many years, we decided to try CCD photometry, but without having to mortgage our houses in order to buy high-end equipment. When Meade Instruments came out with the monochrome Deep Sky Imager DSI™ Pro for under $400, we decided that would be an ideal CCD camera to work with. The price is well within the budget of most astronomers, and the specifications for the camera looked more than sufficient to experiment with CCD photometry. In order to do filter photometry, we added a filter wheel and standard BVRI photometric filters.

When purchasing a DSI Pro camera, the AutoStar Suite™ telescope control and imaging software is included at no additional cost. While there are other CCD software packages on the market, we decided to see just how useful the AutoStar software would be. Although the Autostar documentation serves to get started in astro imaging, it lacks detail in explaining what is needed to perform photometry; and our first impressions were that we should probably look to other programs. But since the AutoStar Suite required no further investment, we decided to go ahead and experiment with the included software. It turns out that the AutoStar Suite is excellent and will do most everything required, and has many additional features over some other CCD software.

Because the Phoenix, Arizona area tends to be very warm to extremely hot (even at midnight) during the warmer months, the ambient air-cooled DSI Pro camera produced higher dark counts than desired. A simple and inexpensive modification to add a thermoelectric cooler was developed, that has proved excellent in not only reducing the dark noise, but also increased the camera sensitivity.

After mentioning our success with the camera modifications and AutoStar software to other astronomers, we received many requests for more information. A web site was created with some of the basics of what we had learned. This included step-by-step Autostar procedures for performing astronomical photometry. Then we decided to combine our skills and expand and share the information – this book is the first result.

We hope this book will help to inspire others to try CCD photometry. While the primary focus is on the Meade DSI Pro cameras and AutoStar software, much of the information applies to any CCD camera and associated computer programs. Once you have set up your equipment and gained some experience, the observations can be very rewarding. Indeed, you may even see your name and data published in professional journals.

JLH and GAL, Phoenix, Arizona April 2007.

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1. Introduction

Astronomical photometry performed with Charge Coupled Devices (CCDs) has the big advantage of being able to acquire simultaneous data on multiple stars. The sensitivity of the CCD allows short exposures on the brighter stars, and also the ability to work with very faint stars. One disadvantage is the low dynamic range of the CCD camera, compared to single-channel photometry such as using photon counting methods. For accurate CCD photometry, the comparison and program stars must be within one or two magnitudes of each other. Photometric imaging is very similar to regular astro imaging, except the images are taken through special photometric filters.

1.1 Learning Stages

1. Learning the equipment – telescope, mount, camera, and software. While most any telescope can be used, reflectors are favored. For the telescope mounting, a fork mount will be superior to a German Equatorial Mount (GEM). This is because the best photometry is performed near the meridian (straight overhead) and that is where the GEMs are weakest, as they must do a "meridian flip" to continue tracking past the meridian. A fork mount has no such problem. A polar/equatorial mounted telescope is preferred to an altitude/azimuth (Alt/Az) mount, although it is certainly possible to do photometry with an Alt/Az mounted telescope. A permanent setup is preferred. If the telescope and camera/filter equipment is removed each night, setting up and aligning can take a fair amount of time. Some protection against wind and stray light is useful. But horizon-to-horizon visibility is not needed. At the most, plus and minus 60 degrees (a cone of 120 degrees with the telescope at the vertex) from the zenith would be fine. In fact, plus and minus 30 degrees will work well most of the time, as that is the best region for photometry.

2. Learning to take good images of star fields involves taking Dark and Flat Fields and using them to calibrate the images.

3. Practicing Photometry – Once you have mastered the imaging steps, you are ready to practice photometry. Pick some stars that are high in the sky when they cross the meridian. The closer to the zenith, the better. The further from the meridian the poorer quality the images will be and thus poorer photometry. Try to plan your observing so that the star is to the East of the meridian and will cross during the observing session.

4. Take multiple sets of images of a star field with a Program and a Comparison star. Be sure to save the images as FITS. If you save the images as a JPG or GIF or other than a FITS format, you cannot do photometry on the image.

5. Practice getting data from a single image until you get consistent magnitude values. The values should repeat exactly for the same image. This may require investigation into the profile of the star image and adjusting the Aperture and Annulus settings. (These settings are discussed in later sections.)

6. Practice getting data from several images of the same star field taken near the same time and with the same filter. The magnitude data on the individual stars should be the same between images. Most likely, the data will not be the same at first. Work to find out why and how to minimize the differences.

7. Once you have **repeatable data and are confident** in knowing what you are doing, **start some serious photometry**.

The following chapters describe suggested procedures for using a Meade® Deep Sky Imager (DSI)™ Pro or DSI Pro-II monochrome CCD camera with the AutoStar Suite™ and Envisage software. Note: Aside from the specific steps involved in taking images with the DSI camera, once images have been acquired with most any CCD camera and stored as standard FITS files, the AutoStar Suite Image Processing software can be used, and the rest of the instructions for photometry also apply.

2. Data Acquisition

Before any photometry can be done on the star, you must first take suitable images. The following steps describe the procedures developed at Hopkins Phoenix Observatory (HPO) using the Meade® AutoStar Suite™ software and a DSI™ Pro or DSI Pro-II monochrome CCD cameras to acquire photometric images.

2.1 Telescope and Camera Setup

Set up the telescope and DSI camera, and connect the cables to your PC. Power up the telescope and align it for tracking. Be sure to uncover the optics. Turn on the PC. (The following instructions assume the **Meade Autostar Suite Software** has been installed.)

2.2 Software Setup

Click on the Autostar shortcut icon and Open the **Meade AutoStar Suite** software. The first window shown (Figure 2-1) is the Planetarium (star map display) program. From the **Image** pull-down menu tab, select **DSI Imaging**.

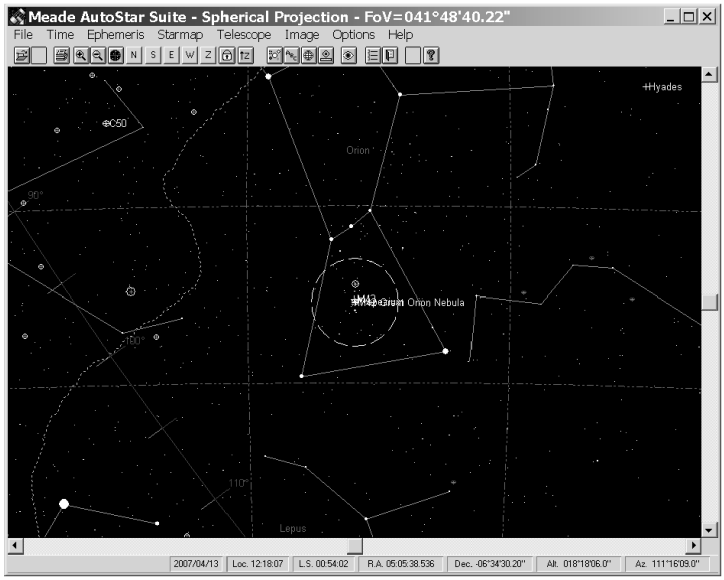

Figure 2-1. Meade AutoStar Suite Planetarium Screen – Selecting DSI Imaging.

The **AutoStar Envisage** window will then open (Fig. 2-2). After a few moments, if there are problems and the camera image doesn't show up, check the USB connection to the DSI camera. You should use a powered USB 2.0 interface, even though the DSI camera will work marginally with USB 1.0. If problems persist, try another USB cable. **Note:** A maximum length of 12 to 16 feet (3.5 to 5 meters) is recommended for the USB 2.0 cable connection to the DSI camera.

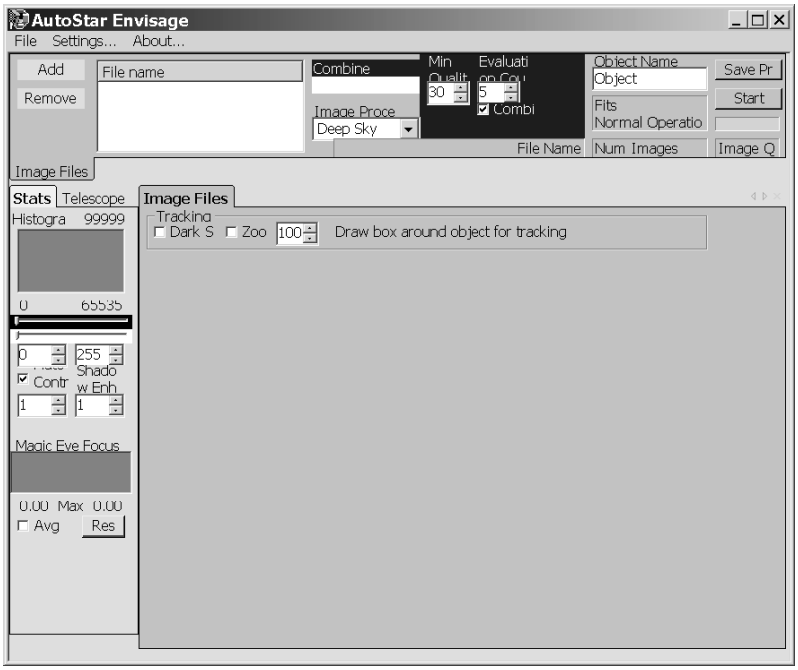

Figure 2-2. AutoStar Envisage Screen -- Selecting Settings. (Camera Not Connected or Inoperative).

Figure 2-2 shows the **AutoStar Envisage** default window, the one that displays when the camera is not recognized (not connected or has a problem). This is easily identified by the "**Add**" and "**Remove**" buttons at the upper left. When the camera is connected and all is working, those are replaced by the "**Gain**" and "**Offset**" sliders. (Also note that the window showing the camera image is blank.) It may be necessary to re-connect the USB cable and camera to a specific USB port, in order for the device to be recognized.

2.3 Setting Directories

Before going further, you may wish to set the **Settings** for the image acquisition program (**Envisage**) for your setup. Select the **Settings** pull-down menu (Figure 2-3).

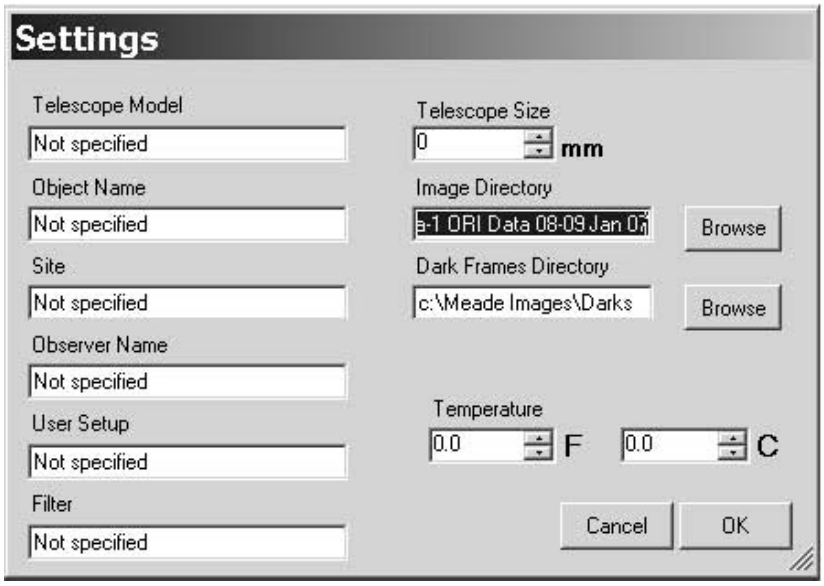

Figure 2-3. Settings Window.

For the **Image Directory** and **Dark Frames Directory,** use the default settings or create new ones. (To avoid confusion until you have gained experience, it is suggested to use the default directories.) Note: The **Temperature** boxes are merely a Fahrenheit-to-Celsius conversion and do not do anything else. Click **OK** when done.

Open the observatory, and set up the telescope and tracking. Turn on the camera and start cool-down/stabilization. Allow 15 minutes or more before proceeding.

2.4 Taking Dark Frames

The following procedure should be performed each evening, prior to starting the imaging. Let the equipment stabilize and adjust to the ambient temperature for at least 15 (ideally 30) minutes before doing this. **Dark Frames** are used in the software to subtract the inherent noise in the camera electronics from the images.

1. From the **Image Process** menu select **Take Darks**. (Fig. 2-4.)

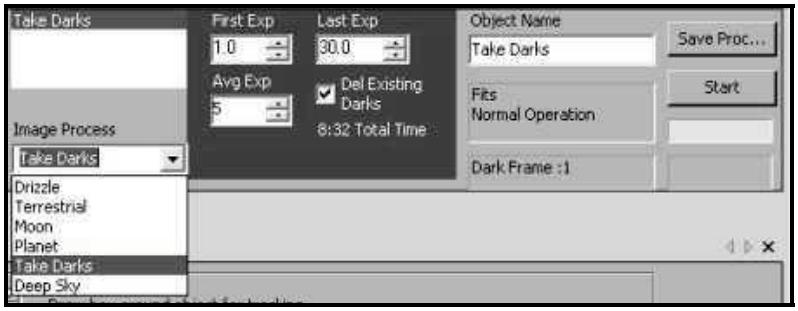

Figure 2-4. Selecting "Take Darks".

Note: The default display in the blue area changes for the one displaying the **Min Quality %**, **Evaluation Count** and **Combine** check box to **First Exp**, **Last Exp**, **Avg Exp** and **Del Existing Darks** check box. **Take Darks** gets put in the **Object Name** field automatically.

2. Set the range of exposure times. The shortest is 1.0 seconds. Set the **First Exp** (in this case 1.0), and set the **Last Exp** (in this case 30.0). These are default settings. This will take Dark Frames for exposure times of1.0 through 30 seconds. If you plan a maximum of say, 15-second exposures, then set the **Last Exp** to 15.

This will shorten the time it takes to make the dark frames. Use the default value of **5** for **Avg Exp** (the **Avg Exp** is the number of images that are averaged and stacked for each exposure time) and select the **Del Existing Darks** check box. An estimated time for taking the dark frames will be shown (for this case, the estimated time for taking the Dark Frames from 1 to 30 seconds is 8 minutes and 32 seconds).

Note: There will be one Master Dark Frame for each exposure 1.0 second or greater (for the times used). You cannot take Dark Frames for exposure times less than 1.0 second; and indeed they normally are not needed for such short exposures. Filters do not enter in for Dark Frames. Since Bias data is part of the Dark Frame, there is no need to take separate Bias Frames. The filter selected does not matter. There may be some light leakage through the filter wheel (or slider), so it is best to do this after it is completely dark. (If necessary, say if the Moon is very bright, cover the filters with a dark cloth.)

3. Click the **Start** button. A **Take Darks** window will pop up, telling you to ***cover*** the telescope objective. (Fig. 2-5.)

Figure 2-5. Take Darks Window.

4. ***Cover*** the front of the telescope and click the **OK** button.

5. The computer will take the Dark Frames automatically. When completed, a **Dark Frames Complete** window will pop up, reminding you to ***uncover*** the telescope. (Fig. 2-6.)

Figure 2-6. Dark Frames Complete Window.

6. ***Uncover*** the telescope and click the **OK** button.

You now have a set of Master Dark Frames for the desired exposure times. These are stored in a folder called **Darks** located in the **Meade Images** folder (unless you designated a different folder).

2.5 Taking Star Images

When taking stellar images for photometry, one of the great features of CCD imaging with the Autostar Suite software is the ability to automatically take multiple short exposure images and stack them. The images can also be automatically aligned with the software. While a single, long-exposure (say, 60 seconds) might be considered to be better than 10 each 6-second exposures, the shorter exposures have advantages. One big advantage of stacking multiple images is that the signal-to-noise (S/N) ratio is improved, while also minimizing any tracking errors.

2.5.1 Imaging Procedure

1. **Find the star field to be imaged** and center the telescope on the first star. Position the **B** filter in the optical path. If you are using an SCT telescope equipped with a mirror lock and an external electric focuser, set the fine electric focus so that the range of movement is about midway between the extremes. Now do a (normal) coarse focus with the telescope manual focuser (the knob that moves the primary mirror). Turn (or drive) the knob CCW past the focus and then CW back to the focus. (Always finish by moving the focus in the same direction.)

Now Lock the mirror (if the telescope has a Mirror Lock). Final focus using the fine motion electric focuser for the sharpest images with the CCD camera.

Figure 2-7 shows a screen shot with the DSI Pro CCD camera connected and working. Check the focus in each of the filters. At HPO, we have found that imaging with the **I** filter seems to be the most critical. If that is focused well, the other filters are usually acceptable also.

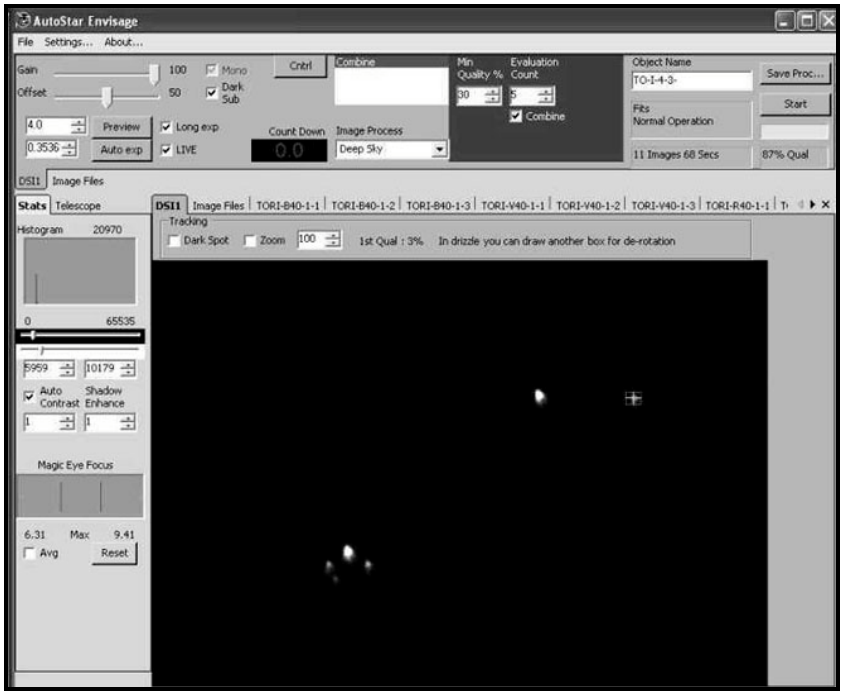

Figure 2-7. Envisage Screen With CCD Camera Operating.

2. **Determine exposure time(s)** that allows reasonable maximum count values for the stars of interest, but less than 65,535 counts. (See Fig. 2-7.) This includes both the program and comparison stars, and in each filter. Do not worry if some of the other field star images are saturated. As long as they are not of interest (in the photometry program) and do not overlap the stars that are of interest, it will not matter. Do not pay any attention to the histogram or other items in the **Stats** area.

Remember, different filters can have different exposure times. Make sure the **Gain** and **Offset** are at the default settings of **100** and **50**, respectively. At these settings, a count of less than 65,535 will be in the linear region of the CCD.

3. **Set the exposure time.** Figure 2-8 shows a screen shot of the area where you can set the exposures.

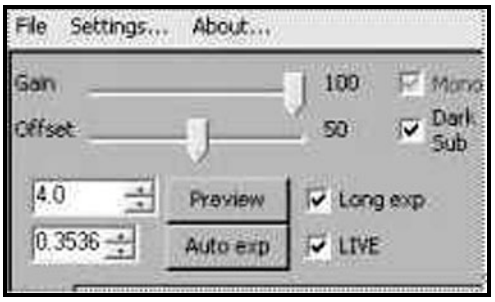

Figure 2-8. Exposure Setting Window.

Note: **Live Exp** exposure times can be set shorter than 1.0 seconds; and **Long Exp** times can be set to steps of 1.0, 1.4, 2.0, 2,8, 4.0, 5.7, 8.1, 11.3, 15, ... seconds. You can use the **Live** exposure time for short exposures (up to 15 seconds). For times greater than 1 second, we suggest using **Long Exp**.

Leave the **Live** button clicked for now.

4. Check the dark field subtraction box (**Dark Sub**).

Note: Leave the **Gain** and **Offset** at their default values (**Gain** = 100, **Offset** = 50). With these settings, the DSI camera produces about 1.43 ADUs/electron. The linear range of the camera is up to about 45,000 electrons; which means with a **Gain** of 100, the ADU count is linear to the maximum 16-bit analog-to-digital (A-D) converter output, or 65,535 counts.

5. In the **Image Process** box (see Figure 2-9) select **Deep Sky**.

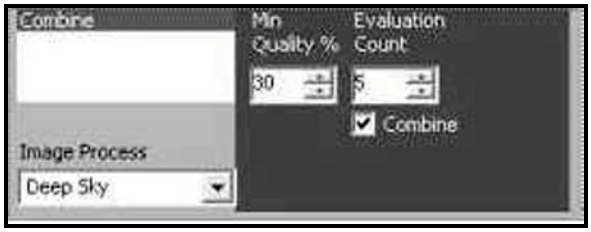

Figure 2-9. Deep Sky Image Process Window.

6. File Naming -- Note: CCD photometry imaging creates an enormous amount of data very quickly. Each image will be over 1.2 MB. It is very important to develop a systematic approach to handling the data and naming of the files. The following procedures is what is used at HPO and is just a suggestion. You can develop your own technique as long as it works for you.

In the **Object Name** field (Fig. 2-7), change the name from "Deep Sky" to the name of the image file for the exposure, e.g., "Star Name"-I-"exposure time"-"Set No."-, e.g., "TO-I-4-3-".

Note: The software will automatically add a sequential number to the end of the file name (e.g., TO-I-4-1-1, TO-I-4-1-2, TO-I-4-1-3, etc. The next set would be TO-I-4-2-1, ...). You cannot use a period in the file name. So for exposure times with a decimal value, just specify the exposure time without the period; i.e., 28 stands for 2.8, 40 for 4.0, 57 for 5.7, or just use 4 for 4 seconds etc., dropping the zero where appropriate.

7. Click the **Save Proc...** button. The **Save Process** window will be shown as seen in Figure 2-10. Make sure for **File Type** that "**Fits"** is selected. For **Save Options** make sure "**Normal Operation"** is selected. Leave the **Single Shot** and **Web Mode** buttons unchecked. Click **OK.**

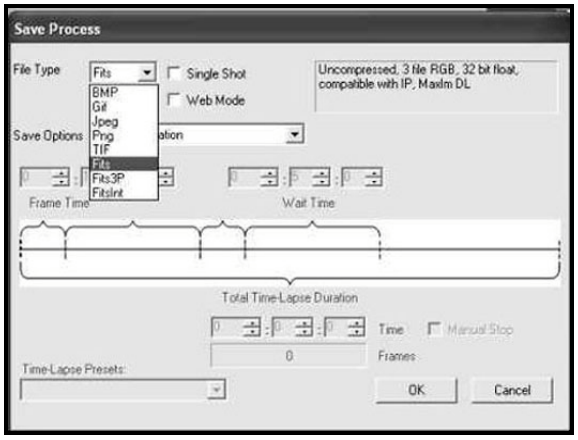

Figure 2-10. Save Process Window.

8. Unless the sky is exceptionally steady, leave the image quality (**Min Quality %**) at **30** and evaluation frames (**Evaluation Count**) at **5**. These default values seem to work well. Check the **Combine** box. (Fig. 2-11.)

Figure 2-11. Quality and Evaluation Count Window.

Make sure the images are saved as **FITS** files and **Normal Operation** is selected (see Fig. 2-12). Click the **Save Procedure** button.

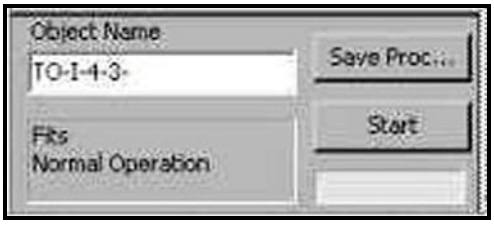

Figure 2-12. Save Procedure Window.

9. Now we will set up a **Tracking Reference Star** that will be used to align the images in the stack of images that are combined. While viewing the real-time image (with the **DSI1** folder tab selected and **Live** box checked; see Figure 2-13), draw a small box around an isolated star to be used as a Reference Guide Star (see Figure 2-14).

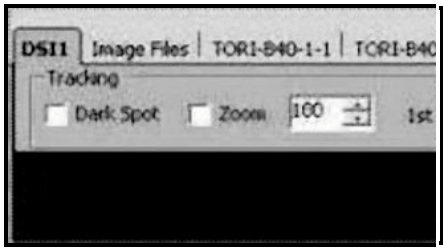

Figure 2-13.
DSI1 Folder Tab.

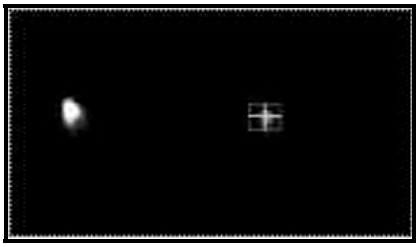

Figure 2-14.
Tracking Star Selection Box.

Note: If an Alt/Az mount is used, a second box can be drawn around another star to derotate the field when stacking (combining) the images. Again, do not worry about anything in the **Stats Area** at this time. That is mostly useful for astro imaging (not photometry). (Fig. 2-15.)

Figure 2-15. Stats Area – (May Be Ignored for Photometry).

10. If a long exposure (greater than 1 second) is used, make sure the **Long exp** check box is selected. (Fig. 2-16.) Set the **Long exp** time, and ***Unselect*** the **Live** box. If you do not ***uncheck*** the **Live** button, that will be the exposure time regardless of what the **Long exp** is set at. Make sure the **Dark Sub** box is still checked. (Note: For the monochrome DSI Pro camera, the **Mono** check box cannot be changed.)

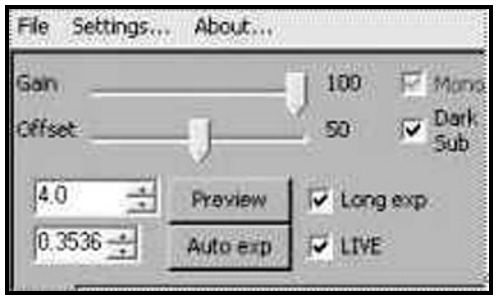

Figure 2-16. Long Exp and Live Selections.
(Note Dark Sub is Checked.)

11. Select **Start**. (Fig. 2-17.)

Figure 2-17. Start Button.

12. After at least 10 images have been combined, select **Stop**. If longer exposure times are used, a lesser number can be stacked. Only images meeting the **Min Quality %** will be included in the combined stack. If the seeing is poor, it may take several minutes to get 10 good images, even with exposures of just a few seconds.

13. Repeat Steps 11 and 12 two more times to produce a set of three stacked image files. This will allow the data to be averaged during the analysis process (described later).

Note: If a failure occurs during imaging, the seeing turns bad, or for some reason not enough images are stacked, just run an additional set.

14. Select the **V** filter and repeat Steps 1 - 13. Name the file(s) "Star Name"-**V**-"Time"-1- etc.

15. Select the **R** filter and repeat Steps 1 - 13. Name the file(s) "Star Name"-**R**-"Time"-1- etc.

16. Select the **I** filter and repeat Steps 1 - 13. Name the file(s) "Star Name"-**I**-"Time"-1- etc.

Note: You should now have three combined/stacked image files for each filter (a total of 12 image files). When the image data sets for each filter are averaged, one data point for each filter will be produced.

17. Repeat Steps 1 - 16 for each additional set of data points desired (for a time sequence, for instance).

Note: Unless changed, the image files will be stored in a folder called **Meade Images**. Find it and make a shortcut to it and put the shortcut folder icon on the desktop for easy use later.

2.5.2 Flat Frames

Flat Frames/Fields provide a calibration for the pixels of the CCD chip, and are used to remove defects (bad pixels), uneveness in the chip response, and shadows from dust particles on the optics. **Flat Field** images are taken just like regular star images; except the telescope front end is evenly illuminated with white light. There are several ways to do this. See Appendix G for information on the suggested design and construction of a Light Box for taking Flat fields. A simple light box seems to work best. One set of flat fields (stacked/combined) must be obtained through each filter.

Sky Flats can be used if taken at the right time, just after or before sunset/sunrise. Aim the telescope near the zenith and turn off the clock drive (otherwise you may have star images even when the sky is still fairly bright). Because the sky brightness changes rapidly during twilight, sky flats must be taken as quickly as possible. **Dome Flats** are a second method, pointing the telescope at an evenly illuminated panel on the inside of the telescope enclosure.

Take as many Flat Field images per filter as practical (10 to 100 is ideal). The brightness of the illumination and/or exposure time may need to be adjusted to get good flats. Adjust the exposure time and/or brightness for at least 10,000 counts on the **Histogram** but less than 65,000 counts (for each filter).

Note: It is very important that the optical train is not changed between imaging and taking the Flat Fields. This means no moving or adjusting of the camera relative to the telescope and only minor focusing. This is why it is usually best to take flats at the end of a session. If the optical path is not identical for the Flat Field images and the star images, the flat fields will be of no value, as they will calibrate against the wrong pixels.

Take a stacked Flat Field image for each filter. Take at least 10 exposures (the more the better) and combine them for each filter. Name these stacked images "FB", "FV", "FR", and "FI", for the B, V, R, and I filter Flats, respectively. (The names are needed to ensure the right Flat Fields are used to calibrate the particular filter images later.) Figure 2-18 shows a sample Flat Field taken using the evening twilight sky and I band filter. (Flats taken in other filters will look very similar.)

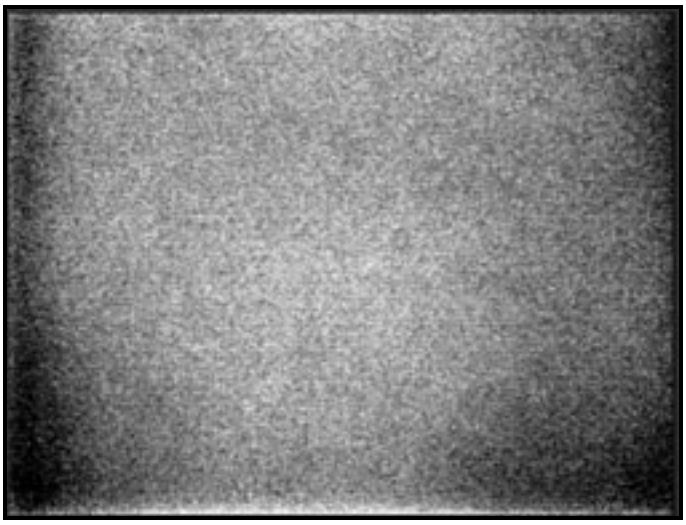

Figure 2-18. Sample I Filter Sky Flat.

3. Raw Data Reduction

This is the stage where the photometric data is extracted from the images. When getting the data from an image, the data will be automatically logged into a text file called **ImageInfo.txt**. The software does a great deal of the work automatically.

3.1 Arranging the Files

The following procedure steps are just suggestions, and you can develop your own scheme, as long as it makes sense and works for you. (Windows software is notorious for putting files in places you do not expect, and thus losing them for you. Experiment to make sure the files are stored where you want them.)

Create a folder with the star name and observation double date in the title, (e.g., TOri 22-23 Jan 07). Create separate folders for the data from each filter (e.g., B Raw Data, V Raw Data, R Raw Data, and I Raw Data). Put the stacked Flat Field image file for each filter in the corresponding filter data folder. Do not worry about the Dark Fields. These have already been subtracted on the fly during imaging.

To simplify finding the proper image files, you can first open an **image** file directly -- this will open the **AutoStar Image Processing** application, then the image file. You should then close the **image** file, but not the **image processing** program. This is done to make sure the **ImageInfo.txt** file is created in the correct folder by the software. Then you may open the specific image file you wish to start with.

Note: You can open the **ImageInfo.txt** file at any time, to check the log, using the **NotePad** program included with Windows. You can also edit the log at any time and save changes. However, do not change the name or location of the file until all the data has been logged in. Experiment some with the following procedures, until you are familiar with the process and how it works. It is very important to know where the **ImageInfo.txt** file is stored, as this is where your photometric data is located.

3.2 Calibrating the Images

1. Click on one of the image files in the new folder. The **AutoStar Image Processing** program will open the file.

2. Close the file, but not the image processing program.

To make working on similar files (taken with the same filter) easier, a **Group** can be created that will have all of the calibration steps done on the members of the **Group** automatically.

3. Click on the **Group** pull-down menu and select **New**. (See Fig. 3-1.)

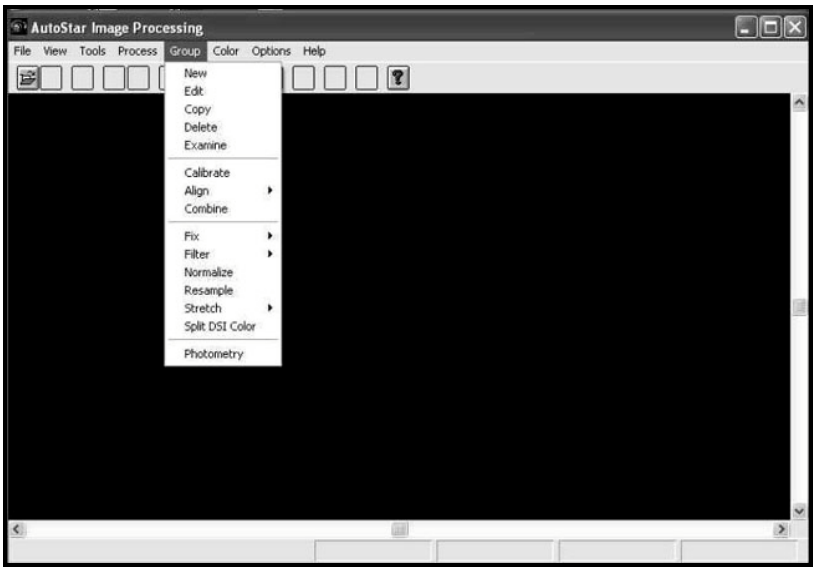

Figure 3-1. Selecting a New Group of Images.

Note: The **Photometry** selection in this window is a bit misleading. It's designed to automate time-series projects where you may have hundreds of images taken in each filter. For starting out, this can cause more problems than it solves. Ignore it for now. Also, you may ignore the rest of the items from this pull-down menu, as they mainly apply to astro imaging and not photometry.

4. Select all the images of a given filter (e.g., the V filter images in the V Raw Data folder). (See Fig. 3-2.)

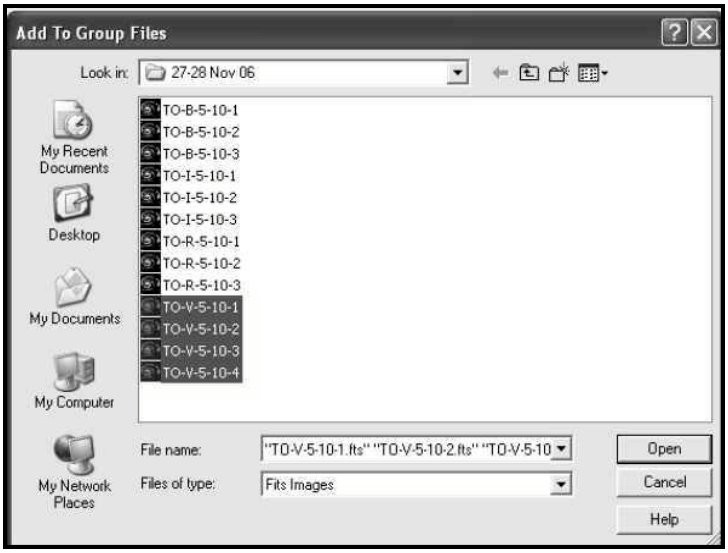

Figure 3-2. Selecting Filter Files to Calibrate with Flat Field.

Note: This will create a new text file called **ImageGroup.lst**. Do not move or rename this file. This is not a text file and cannot be opened. Just let it be, as it defines the files in the Group.

5. From the **Group** pull-down menu, select **Calibrate**. (Fig. 3-3.)

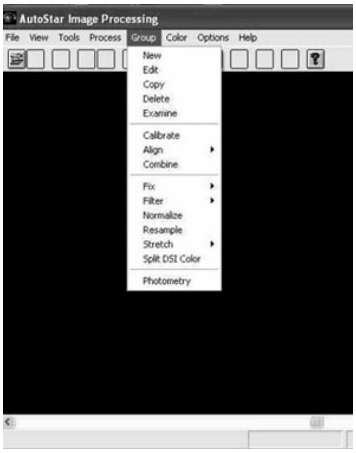

Figure 3-3. Calibrate Selection.

6. A **Calibrate** window will be displayed (Fig. 3-4) where you can select and include a Bias, Dark Frame, and a Flat field image. If you have used the Auto Dark Subtraction option while taking images, or if the exposure time is less than 1 second, you do not need to use another dark frame. If you have used a dark frame when taking the images, the Bias image is not needed.

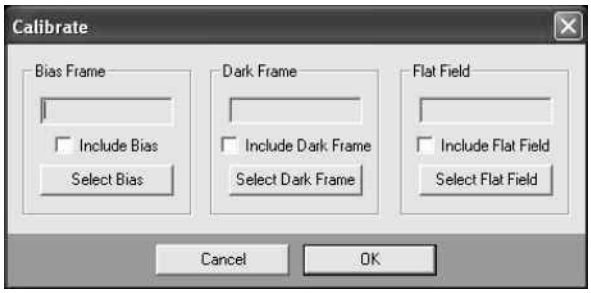

Figure 3-4. Calibrate Window.

Note: This will create a new file called **NewImageGroup.lst**. Do not move or rename this file. This is not a text file and cannot be opened. Just let it be, as it defines the **Calibration** for the files in the **Group**.

7. Select the **Flat Field** you wish to use to calibrate with (e.g., click on **Select Flat Field** and find the flat field for the filter used for the images to be calibrated – for instance, **FV** for the **V** filter images). Click the **Include Flat Field** box, and if desired the **Include Bias** button (after selecting the **Bias** image). Remember that the **Dark Frame**s have already been used on the fly when the images were exposed (if the Auto Dark Subtract option was selected). Also, the **Bias Frame** data is included as part of the **Dark Frame**. Click on **OK**.

8. The program will now automatically calibrate all the images and save the newly-calibrated images with new names (e.g., **Calibrated_"file name"**). The original (uncalibrated) images will be left untouched. (See Fig. 3-5.)

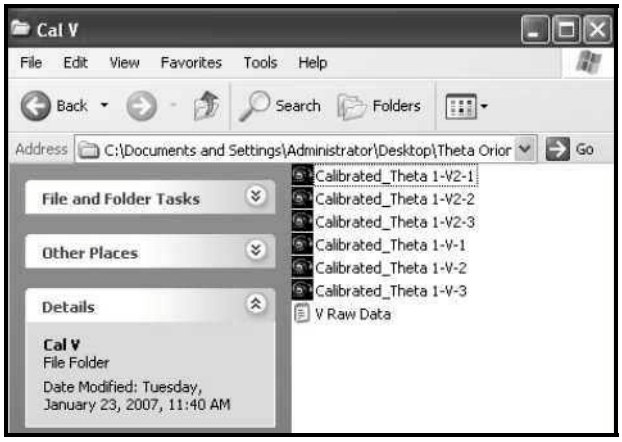

Figure 3-5. New Calibrated Image Files.

9. To organize the calibrated files, make a new folder within the current folder. Call this folder "**Cal Filter Name Data**" (**or** "**Cal V**" for the **V** filter calibrated images).

10. Repeat steps 3 through 9 for each of the other filters. You now have sets of calibrated data ready to have the star magnitudes determined.

3.3 Differential Magnitudes

The best and most accurate way to do photometry is to use differential photometry, in which Program star magnitudes are compared against known Comparison star magnitudes and then normalized to produce a differential magnitude. This means you must know the Comparison star Reference magnitude accurately for each filter band.

3.3.1 Setting the Reference Magnitude

1. From within the Autostar Image Processing program, select **File** and **Open.**

2. From within the **Cal V** folder (e.g., the Calibrated **V** filter images) select the first image to be processed. Make sure the file name has "**Calibrated**" in front of it.

Note: AutoStar automatically adjusts the monitor display contrast; so even if the images look faint, the data should be okay. If the star image is too faint to be easily seen, you can adjust the contrast manually. The adjustment only affects the display. You can also expand the image to full screen if it helps.

3. Start by drawing a small box around the Comparison star. There will be a diagonal line across the (inner) box. The box should be placed so that the line is approximately across the middle of the star image. This is not very critical, as the software will find the center of the star (the "centroid"). (See Fig. 3-6.) The direction used to draw the box is up to you.

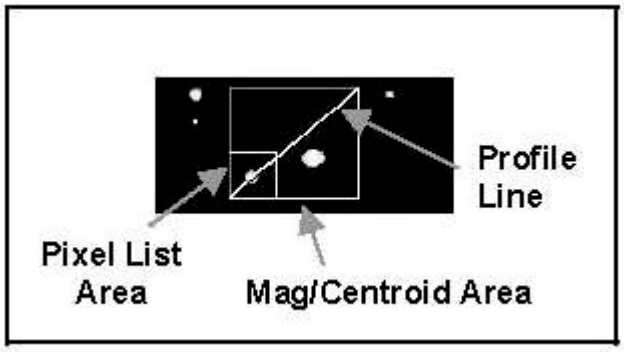

Figure 3-6. Photometry Cursor.

Note: The Photometry region cursor has three main components (Fig. 3-6):

(a) Magnitude/Centroid Area
(b) Pixel List Area
(c) Profile Line

The **Magnitude/Centroid** rectangle bounds the entire area used in the magnitude and/or centroiding calculations. This is a bit confusing – to properly determine the magnitude of a star, **only** draw the small box (shown to the lower left – the **Pixel List Area**) around the star of interest. The **Profile line** delineates the pixels that will be displayed when the **Draw Profile** function is selected.

You will see the term "centroid" appear many times when reading about CCD photometry. This is a bit of software "magic". The centroid of a star image is essentially its center of gravity or center of brightness. The CCD software can find this center very precisely. This is important, because when selecting the star for processing, you do not need to select it exactly. Just as long as you are close, the software will find the center (centroid) of the star and reference everything about the star relative to that center. This is also important when using the CCD camera for tracking, as the star image center can be determined precisely.

4. In the pop-up window, select **Set Reference Magnitude**. (Fig. 3-7).

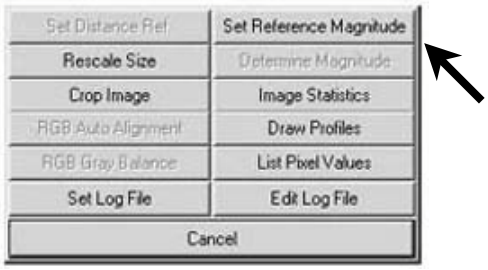

Figure 3-7. Select Set Reference Magnitude.

5. Set the **Reference Magnitude** for the Comparison star for that filter and Click **OK**.. (Fig. 3-8.)

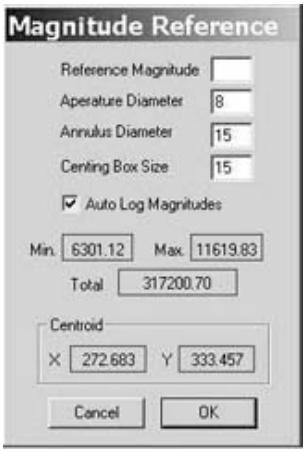

Figure 3-8. Set Reference Magnitude Window.

Note: This will set the Reference magnitude for the Comparison star. This action must be performed with each image. The other star measurements will now produce magnitude values referenced to the Comparison star Reference magnitude that was entered. This will create a new text file in the folder called **ImageInfo.txt**. All the data that is acquired from the images will be logged into that file. Do not move or rename the file until all of the data (for all the filters) has been entered.

3.3.2 Aperture Diameter, Annulus, and Centering Box Size Settings

The **Aperture Diameter**, **Annulus,** and **Centering Box Size** can be changed, but unless you want to experiment or know what you re doing, it is best to leave these values at their default settings of 8, 15, and 15, respectively.

3.3.3 Raw Magnitude Determination

6. Draw a box around the first Program star. A widow will pop up. Select **Determine Magnitude**. (Fig. 3-9.)

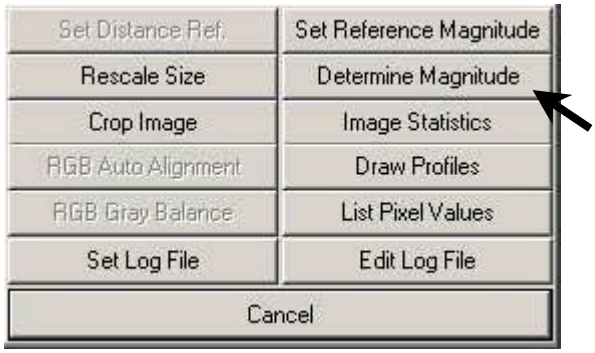

Figure 3-9 . Select Determine Magnitude.

7. A **Magnitude Determination** window will be displayed, indicating the selected Program star magnitude referenced to the Comparison star, along with other data. (Fig. 3-10.)

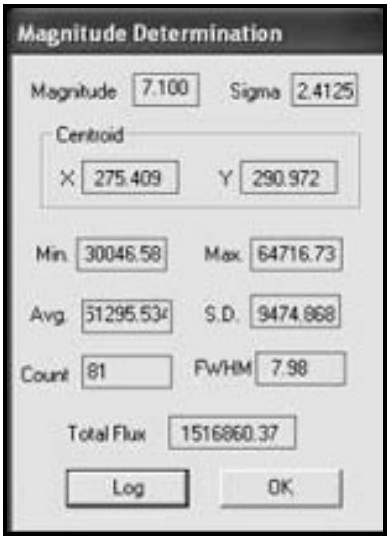

Figure 3-10. Magnitude Determination Window.

8. Click on **OK**. Do not click on "**Log**"**,** as the data will be logged twice. Just click **OK.**

9. Repeat Steps 1 - 8 for each Program star you wish to know the magnitude of.

10. As a double-check and a way to indicate where you are in the Log file, determine the magnitude of the Comparison star as the last measurement. It should be the same as what was set earlier for the Reference magnitude.

Note: To continue with additional images *taken with the same filter*, repeat Steps 1 - 8; but you will not need to re-enter the Reference magnitude value as it is already set (for that filter), so just click **OK** for that step. You will need to use the **Set Reference Magnitude** with each image, however.

11. When done, you should have data from all the images for the given filter. You should also have a single text file called "**ImageInfo**." You now can rename the text file. Call it "**V Data.txt**" (for the **V** filter images.)

12. Repeat Steps 1 - 11 for the other filter images. A text log file called **ImageInfo.txt** will be created.

3.4 ImageInfo File

The **ImageInfo.txt** file is a text file that is automatically created when determining the magnitudes of the stars. Table 3-1 shows a screen shot of a sample file.

Table 3-1. ImageInfo Log Text File Example.

```
File: C:\Meade Images\BVRI 25-26 Jan 07\Calibrated_TOB-1-1.fts
X Center  Y Center  FWHM Magnitdue Sigma    Flux       Min
  246.70    355.30  6.28  6.6688  0.2018  381773.4   7267.17
  255.43    369.35  5.86  8.2451  0.3672   89382.8   6775.37
  265.34    338.44  6.38  5.1507  0.2419 1545352.4  11742.73
  546.68    147.23  5.64  6.2337  0.2049  569946.2   7683.23
  287.65    350.31  6.38  6.7800  0.2480  344594.4   7525.43

  Date: /2007/2064   Time: 03:53:53
   Max   Average  Std. Dev.        Region        Pix Cnt.
18180.63 12135.375  2830.265 (239, 349)-(254, 364)  256
 9486.22  7878.986   754.094 (264, 376)-(251, 366)  154
56014.24 31931.829 11639.649 (279, 330)-(253, 352)  621
25020.99 14927.225  4528.045 (556, 140)-(539, 154)  270
17596.40 11968.677  2726.206 (299, 342)-(279, 358)  357
```

The **X** and **Y Center** data helps identify which star the data applies to. Regarding the rest of the data: the **Magnitude**, which is relative to the Reference Magnitude, **Flux,** and **Max** are the data of most interest. The **FWHM** (Full Width Half Maximum) number gives an idea of the shape of the star image. If this gets too far away from approximately 6, there may be a problem with the data. The rest of the data may be of interest for determining the quality of the data.

4. Additional Data Reduction

The raw magnitude data now must be used to calculate the average magnitudes and data spread or standard deviations, in addition to calculating the Air Mass and Heliocentric Julian Date (HJD). A Mean time for the set of exposures is also calculated. There are various ways to do this, but since it is time-consuming, it is best to use a computer program. A spreadsheet program can be used (such as Microsoft Excel™), but a much better way is to use a database program such as FileMaker Pro™. Since you will be dealing with a vast amount of data, it is worthwhile learning to use a program like FileMaker Pro so you can develop and customize your database programs as needed.

4.1 DATABASE PROGRAM

The following example database was developed with FileMaker Pro at HPO. Figure 4-1 shows a screen shot of one of the layouts of the FileMaker Pro program. This one is designed specifically for Theta 1 Orionis data (an interesting eclipsing binary star in the Trapezium in Orion). The white data fields are data entry fields and the colored (shaded) fields are auto entry and calculated data.

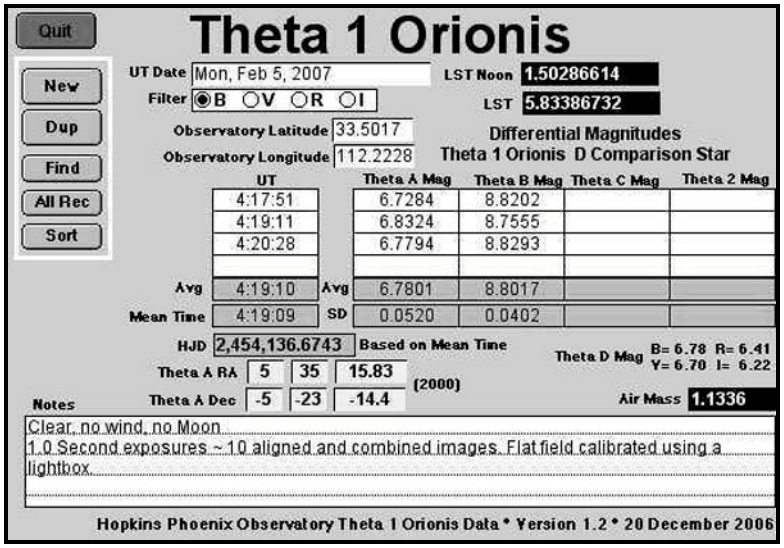
Quit
Theta 1 Orionis
New
Dup
Find
All Rec
Sort
UT Date Mon, Feb 5, 2007
LST Noon 1.50286614
Filter B V R I
LST 5.83386732
Observatory Latitude 33.5017
Observatory Longitude 112.2228
Differential Magnitudes
Theta 1 Orionis D Comparison Star
UT
Theta A Mag
Theta B Mag
Theta C Mag
Theta 2 Mag
4:17:51 6.7284 8.8202
4:19:11 6.8324 8.7555
4:20:28 6.7794 8.8293
Avg 4:19:10 Avg 6.7801 8.8017
Mean Time 4:19:09 SD 0.0520 0.0402
HJD 2,454,136.6743 Based on Mean Time
Theta D Mag B= 6.78 R= 6.41 V= 6.70 I= 6.22
Theta A RA 5 35 15.83 (2000)
Theta A Dec -5 -23 -14.4
Air Mass 1.1336
Notes
Clear, no wind, no Moon
1.0 Second exposures ~ 10 aligned and combined images. Flat field calibrated using a lightbox.
Hopkins Phoenix Observatory Theta 1 Orionis Data * Version 1.2 * 20 December 2006

Figure 4-1. FileMaker Pro Data Summation Program.

This program was created quickly and saves a great deal of work when summarizing the data. The white data fields are data entry fields and the green and black shaded entries are calculated data fields. Data fields have been created for up to 4 program stars. Data fields shaded in blue are global fields used for all the records. The RA and Dec star position values are used in determining the Air Mass and HJD (Heliocentric Julian Date). Since the stars in this project are all located close together in the image, only one star's RA and Dec need be used.

4.2 DATA LIST

A summary list of the data can be easily generated and displayed or printed. Data can be found by any field or combination and sorted in various ways. Figure 4-2 is a screen shot of a report layout in the FileMaker Pro program.

Theta Orionis

Filter	HJD	UT Date	Mean UT	Theta A		Theta B	
				Avg	SD	Avg	SD
B	2,454,073.7587	12/04/2006	6:20:48	**6.7763**	0.0088	**8.4994**	0.0161
B	2,454,073.7663	12/04/2006	6:31:38	**6.7568**	0.0172	**8.4731**	0.0070
B	2,454,064.7693	11/25/2006	6:36:00	**6.7107**	0.0341	**8.2470**	0.0369
B	2,454,065.7741	11/26/2006	6:42:55	**6.7355**	0.0161	**8.5875**	0.1133
B	2,454,066.7701	11/27/2006	6:37:08	**6.7531**	0.0138	**8.5568**	0.0406
B	2,454,070.7716	12/01/2006	6:39:18	**6.6939**	0.0790	**8.5183**	0.1648
B	2,454,070.7732	12/01/2006	6:41:37	**6.6928**	0.0433	**8.5059**	0.0868
B	2,454,070.7852	12/01/2006	6:58:55	**6.7575**	0.0351	**8.3148**	0.0234
B	2,454,070.7943	12/01/2006	7:12:03	**6.7718**	0.0306	**8.3786**	0.0526
B	2,454,071.7075	12/02/2006	5:06:56	**7.2288**	0.0050	**8.3308**	0.0344
B	2,454,071.7163	12/02/2006	5:19:43	**7.2189**	0.0202	**8.2494**	0.0032
B	2,454,071.7367	12/02/2006	5:49:01	**7.3332**	0.0119	**8.2951**	0.0417
B	2,454,071.7477	12/02/2006	6:04:56	**7.3311**	0.0359	**8.2548**	0.0483
B	2,454,071.7589	12/02/2006	6:21:04	**7.3999**	0.0426	**8.2414**	0.0286
B	2,454,071.7670	12/02/2006	6:32:39	**7.4419**	0.0182	**8.2376**	0.0110
B	2,454,071.7756	12/02/2006	6:45:05	**7.4678**	0.0053	**8.2588**	0.0115
B	2,454,071.7823	12/02/2006	6:54:39	**7.4559**	0.0222	**8.2238**	0.0157
B	2,454,071.7904	12/02/2006	7:06:20	**7.5172**	0.0185	**8.2592**	0.0153
B	2,454,071.7995	12/02/2006	7:19:25	**7.5345**	0.0054	**8.2281**	0.0053
B	2,454,071.8072	12/02/2006	7:30:34	**7.5686**	0.0091	**8.2393**	0.0121
B	2,454,071.8142	12/02/2006	7:40:35	**7.6116**	0.0184	**8.3007**	0.0386
B	2,454,071.8219	12/02/2006	7:51:42	**7.6139**	0.0131	**8.2430**	0.0118
B	2,454,071.8289	12/02/2006	8:01:49	**7.6742**	0.0101	**8.2694**	0.0033
B	2,454,071.8353	12/02/2006	8:11:00	**7.6461**	0.0115	**8.2287**	0.0151

Figure 4-2. Database List of Data Records.

5. Advanced Data Reduction

5.1 Reducing the Raw Magnitudes to Standard Magnitudes

So far all or our work has produced raw (instrumental) magnitudes that are unique to the equipment used to produce them. Raw magnitudes are fine, if you are only interested in changes. Many times, data may be desired to be combined with data taken with other equipment. Calibrating the data to a standard will allow it to be useful. Once calibrated, your data will represent true magnitudes. To do this, the raw magnitudes must be corrected with color transformation coefficients. See Appendixes C and D for the details on determining these coefficients.

5.2 Transformation Coefficient Equations

$$(R - I) = \gamma * (r - i) - k'_{ri} * X + \zeta_{ri}$$
$$(V - I) = \alpha * (v - i) - k'_{vi} * X + \zeta_{vi}$$
$$(V - R) = \beta * (v - r) - k'_{vr} * X + \zeta_{vr}$$
$$V = v + \varepsilon * (B - V) - k'_{v} * X + \zeta_{v}$$
$$(B - V) = \mu * (b - v) - k'_{bv} * X + \zeta_{bv}$$

Where:

Instrumental Magnitudes

Instrumental Magnitude = $-2.5 * \log_{10}$ (Star Counts)

i	**v**
r	**b**

Corrected Magnitudes

I	**V**	**(V – I)**	**(V – R)**
R	**B**	**(R – I)**	**(B – V)**

Transformation Coefficients (Must be determined)

α for (V – I)	**ε for V**
β for (V – R)	**μ for (B – V)**
γ for (R – I)	

Extinction Coefficients
(Not needed for differential photometry)

k'_{vi} for (v – i)	**k'_{v} for v**
k'_{vr} for (v – r)	**k'_{bv} for (b – v)**
k'_{ri} for (r – i)	

Zero Points
(Not needed for differential photometry)

ζ_{vi} for (V – I)	**ζ_{v} for V**
ζ_{ri} for (R – I)	**ζ_{bv} for (B – V)**

Note: While Extinction and Zero Points are not needed for differential photometry, they are needed to determine the color transformation coefficients.

The equations for CCD Differential Photometry then simplify to the following:

$(R - I) = \gamma * (r - i)$	**$V = v + \varepsilon * (B - V)$**
$(V - I) = \alpha * (v - i)$	**$(B - V) = \mu * (b - v)$**
$(V - R) = \beta * (v - r)$	

Once the color transformation coefficients have been determined, they can be used along with the raw magnitudes to produce corrected magnitudes.

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NOTES

APPENDIX A
Modifying the DSI Pro Camera

Introduction

The color versions of the Meade Deep Sky Imager (DSI) CCD camera cannot be used for astronomical filter photometry, but the monochrome DSI Pro (and DSI Pro-II) can. To do serious work requires some simple modifications to the camera. These modifications include replacing the stock filter slide with a filter wheel (or turret), and adding a simple thermoelectric cooler (TEC). With these modifications, the DSI Pro (and DSI Pro-II) provide the means to do professional-level astronomical photometry with a modest telescope, even in a light-polluted suburban location. This chapter describes these modifications and what is needed to do BVRI CCD photometry with the camera.

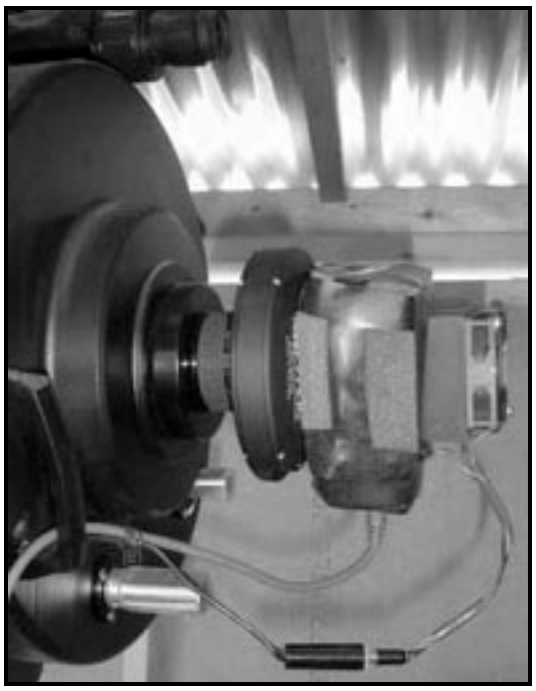

Figure A-1. Modified DSI Pro CCD Camera and Filter Turret on Meade 12 inch (30.5 cm) LX200 GPS Telescope at HPO.

The Affordable Meade Deep Sky Imager (DSI)

While CCD cameras for astronomical use have been around for more than a decade, it has only been recently that affordable and easy-to-use CCD devices have been made available to the amateur market. Some of the first of these were digital web cams. Some folks figured them out and made modifications that produced surprisingly high-quality results. But web cams work best on the brighter objects such as the planets, the Moon, and solar imaging. For deep-sky imaging, the web cams need to be modified, but these modifications are beyond the capability of many amateurs.

When Meade introduced the color Deep Sky Imager (DSI), that changed. Now one could do deep-sky imaging of faint objects without needing to make complicated modifications to the camera. In addition, the AutoStar Suite software that comes with the DSI series is excellent. It's worth the price of the camera alone. Learning the software requires some dedication, as the quality of the software far exceeds the documentation (thus, this book!)

However, two technical issues prevent use of the color versions of the DSI camera for effective astronomical filter photometry. Because the Sony HAD EX-View® color CCD chip used in the DSI color version has built-in microlens red-green-blue (RGB) filters on the photosites, it would be hard or impossible to find proper filters to match the camera to the standard photometric system. The other issue, while mainly a problem only during the warmer months, is that the DSI camera is electrically uncooled and operates at ambient temperature.

Monochrome Deep Sky Imager Pro (DSI Pro)

Shortly after the color DSI was released, Meade introduced a monochrome version, the DSI Pro. The monochrome DSI Pro and the newer DSI Pro-II cameras provide a good starting point for serious CCD photometry at moderate expense. Because these cameras use a monochrome version of the Sony CCD chips, a four-position filter slide for RGB filters is included, for tri-color imaging (plus a "clear" or IR blocking filter).

The set of standard RGB astro imaging filters is provided at extra charge. The advantages of using the DSI Pro with the external filters are that the monochrome camera is more sensitive, and provides better resolution, as well as allowing use of different filters.

While the included filter slide could be used to hold photometric filters, it quickly becomes apparent that is not a good idea. The specialized BVRI photometric filters are expensive, and the filter slide is of open construction, exposing the filters to dust, dew, fingerprints, and scratches. A filter wheel (turret) is a much better way to hold and protect the filters.

Adding a Filter Wheel – Installing the Nose Piece Adapter

The first step in readying the DSI Pro for photometry is to replace the stock filter slide holder with a low-profile adapter plate similar to that used on the color DSI (see Figure A-2). This gets rid of the large openings where the slide goes and also reduces the distance from the filters to the CCD chip. The adapter is threaded for standard TEE thread accessories. In the U.S. this adapter plate can be purchased for about $40 from **ScopeStuff**. (See the list of suppliers at the end of this Appendix.)

Note: The original standard TEE threaded to 1.25 inch (31.7 mm) nose piece can also be used with the new adapter, but it's better to mount the filter wheel closer to the camera than allowed by the nose piece. The filter wheel we describe comes with TEE thread couplers for the purpose.

Replacing the original filter slide holder adapter with the low-profile adapter plate is very simple. There are four small Phillips-head screws that hold the adapter in place. Those screws and the original adapter are removed and replaced with the low-profile adapter using new shorter screws (provided).

Note: There are four hex-head screws at the corners of the camera. The hex-head screws hold the camera together. Do not remove those screws for this modification.

Figure A-2. DSI Pro Camera with Filter Slide (left) and Low-Profile and Original Nosepiece Adapters (Right).

Filter Wheel

With the low-profile nosepiece adapter installed on the DSI Pro, the next step is to add a filter wheel. There are several available on the market, ranging from under $100 to over $1,000. An excellent and inexpensive choice is the ATIK Manual Filter Wheel. This can also be purchased from **ScopeStuff** or from **Adirondack Astro Video** (the U.S. importer) for about $200. The ATIK filter wheel is well-made and can hold up to five standard 1.25 inch (31.7 mm) screw-in filters. Figure A-3 shows the ATIK Filter Wheel disassembled and the filter carrier disk with photometric filters installed. The ATIK wheel uses standard TEE threaded adapters (provided) to attach it to the low-profile nose piece on the camera. It also comes with a removable standard 1-1/4 inch (31.7 mm) to TEE thread nose piece.

Since the U band filter is not used with the DSI CCD camera, an optional filter such as Hydrogen Alpha could be placed in the fifth position, or the “Clear” (IR Block) filter that comes with the DSI camera can be installed, for occasional regular deep-sky imaging or “white light” photometry.

Figure A-3. Disassembled ATIK Filter Wheel.

CCD Photometric Filters

For most photometry, special filters must be used. The red, green, and blue (RGB) astro imaging filters supplied for the DSI Pro and DSI Pro-II cannot be used as photometric filters. These are color interference layer coated (dichroic) filters. For CCD photometry, sets of five dyed glass photometric filters – Ultraviolet (U), Blue (B), Visual (V), Red (R), and Infrared (I) are available, conforming to the Johnson-Cousins standard passbands.. While there are other filters, these are the most commonly used in astronomy.

But unless you are planning on using a meter-sized telescope, the U filter will not be of much value, as the DSI Pro (and DSI Pro-II) Sony HAD Ex-View™ CCD chips are not sensitive in that band. Plan on using just the BVRI filters. There are several places you can buy the special dyed glass photometric filters. **Astrodon** offers the least expensive yet good quality filters, at about $310 for a set of **Schuler BVRI Photometric** filters.

Figure A-4 shows the ATIK filter wheel disk with BVRI filters installed in positions 1, 2, 3, and 4, respectively. Position 5 could be used for a U filter, but because the CCD camera chip is insensitive in that band, the Meade IR blocking ("Clear") filter is used, for deep sky imaging or "white light" photometry.

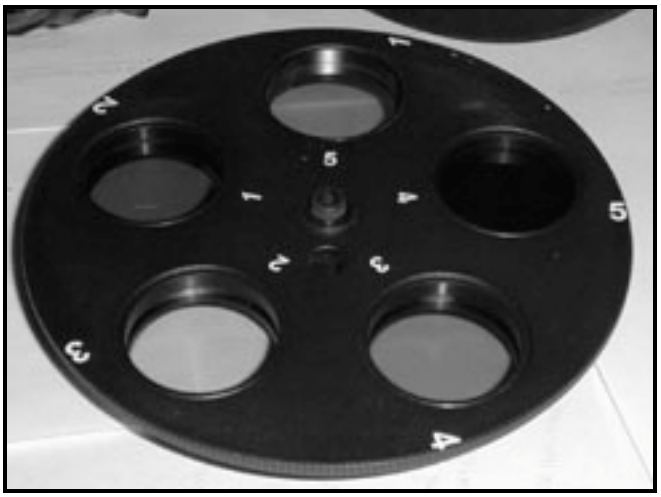

Figure A-4. Filter Wheel Disk with BVRI Photometric Filters.

Table A-1 lists the standard UBVRI Johnson-Cousins system filter bandwidths, measured at the half-height point. Figure A-5 shows the standard UBVRI filter passbands, plotted in Ångstroms. (10 Ångstroms = 1 nanometer.) **Note:** U band work is not practical with most amateur CCDs and is only noted for reference here.

Table A-1. UBVRI Filter Bandwidths.

Band	Center	Width
U	367 nm	66 nm
B	436 nm	94 nm
V	545 nm	88 nm
R	638 nm	138 nm
I	797 nm	149 nm
Bandwidths measured at half-height point.		

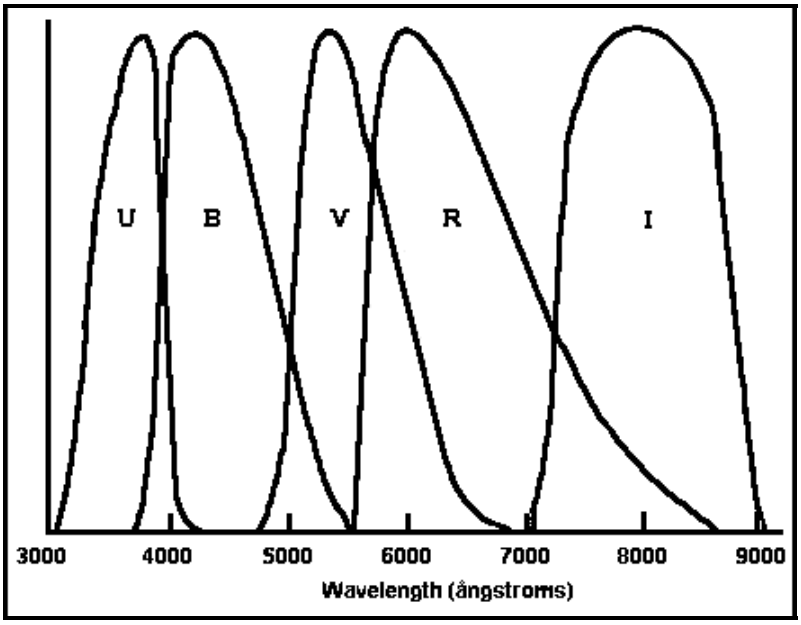

Figure A-5. Standard UBVRI Johnson-Cousins Photometry Filter Passbands.

Cooling the DSI Pro

The DSI series cameras use ambient air cooling. The camera case is equipped with an internal "cold finger" that transmits heat from the CCD chip to the backplate, which acts as an efficient heat exchanger. With cool night time temperatures, these units perform well. However, Dark Frames must still be created and subtracted from each image to get rid of "hot" pixels and thermal noise. During the summer months in Phoenix, Arizona observatory temperatures can approach 100°F (38°C) at midnight. At those temperatures, even subtracting dark frames does not work well.

Adding cooling to the DSI Pro started as an experiment at HPO to see what could be done at minimum cost and the least amount of modification.

This cooling modification can be used on all the DSI series cameras. In addition to reducing dark current, electronic cooling increases the camera's sensitivity.

TEC Cooler Mods

Perhaps the most effective way to cool the CCD is by using a Peltier Junction Thermoelectric Cooler (TEC). Peltier Junction TECs are fascinating devices. They consist of a sandwich of semiconductors connected in parallel, between two metallic plates. By applying a DC voltage across the device, one plate gets hot while the other one is cooled. The amount of heat and cooling produced can actually be surprising! Care must be taken when experimenting so that the unit doesn't overheat. Attaching a finned heatsink and a fan is very important on the hot side. Thermal grease needs to be applied on both plate surfaces to provide effective transfer of the heat (and cooling).

Some will note that there is no temperature regulation or sensor included in our mod. These features could be added, but would increase the complexity. The lack of temperature regulation has not been a problem at HPO. If the camera is allowed to run with power and cooling ON for 15 to 30 minutes, the temperature will stabilize. The exact temperature is not important. Once the unit has stabilized, new dark frames for that evening should be taken. This procedure works well.

Note: The modifications described here involve opening the camera case to install the equipment, and probably will **void the camera warranty**. Some experience with electronics or kit building is highly recommended. A bolt-on TEC cooler backplate assembly is available commercially. A simple clip-on 12VDC electric fan is also available as a standard accessory from Meade, which will lower the camera temperature about 9°F (5°C).

Parts List

The following List of Parts, available from **All Electronics** is recommended. (Catalog prices listed are as of Spring 2007):

Part Name	P/N	Price
40 mm 12VDC Thermo Electric Cooler	PJT-7	$14.75
Heat Sink with 12 VDC Fan	CF-215	$7.50
12 VDC, 3.5A Power Supply	PS-1231	$15.85
Tube of Thermal Grease	TG-20	$4.25

You will also need several 6-32 x 1 inch nylon (non-conducting) screws, some wire, and a power connector. You can get the miscellaneous parts at a local store such as Radio Shack for a couple of dollars. Total cost for the electronic parts is under $50.

DSI Pro TEC Cooler Modifications

Modifications to the DSI Pro camera require opening the camera and drilling holes through the back of the case for two 6-32 screws (for added stability, 4 screws could be used) to hold the TEC/Heat Sink and Fan assembly against the back of the DSI case. **Note: This will void the camera warranty.** Use a 2.5 mm Allen wrench and carefully open the camera from the front by removing the hex-head screws in the corners. Be careful not to tear or stretch the rubber gasket (see Figure A-6).

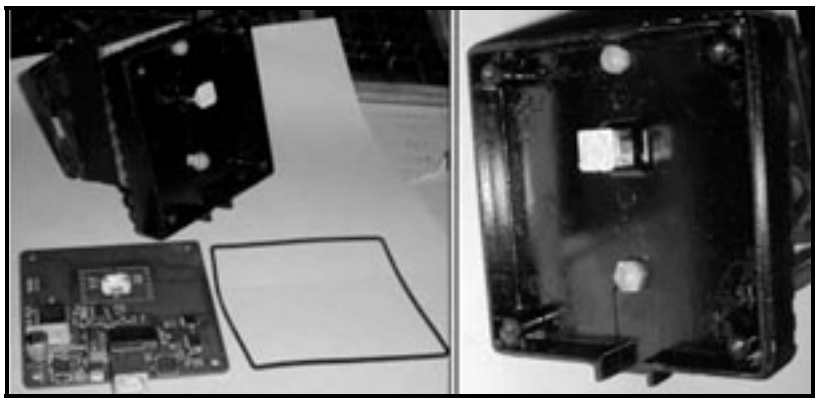

Figure A-6. Views Inside the DSI Pro with Cold Finger (White Square) and Nylon Mounting Screws Shown. Circuit Board and Gasket Below.

Now place the center of the TEC (against the camera back) so it is directly opposite the cold finger (on the inside of the case). Drill and tap 2 (or 4) matching holes through the camera case and into the heat sink. Make sure the hole spacing is sufficient to clear the TEC. Use two nylon (or non-conductive) screws to hold the heat sink/TEC to the back of the camera. The purpose of the non-conducting nylon (plastic) screws is to reduce or prevent heat transfer from the hot heat sink back to the case.

Carefully reassemble the camera, without tearing or damaging the rubber sealing gasket, and tighten the four hex head screws on the front to close the case. Add some foam for insulation around the camera to keep it cool. See Figure A-7 for a view of the modified camera with foam insulation added.

Figure A-7. Modified DSI Pro with Focal Reducer, Filter Wheel, TEC/Heat Sink/Fan Assembly and Foam Insulation.

The optional Meade Series 4000 Focal Reducer lens shown in Figure A-7 provides a larger field of view for the imager. This makes finding the stars and getting comparison stars in the same view much easier.

Wiring and Schematics

The polarity of the TEC is a bit ambiguous, but you can't damage it by reversing the connections. After connecting the power supply, check to verify which side gets "hot" and place that side against the finned heat sink (away from the camera back). Don't forget to apply ample thermal grease between the TEC plates and the camera back, and also to the finned heatsink.

A 12VDC fan is installed on the back of the heatsink, to draw additional cooling air through the fins. At HPO, a 3.5 A 12VDC supply was used, separate from the telescope power, operating from 110VAC. For a portable setup, a 12VDC battery supply could be used. A power indicator light, an ON-OFF switch, and a fuse could be added, or the power supply can simply be unplugged when the camera is not in use (as shown in the illustrations).

Figure A-8 shows drawings of the mechanical modification and an electrical wiring schematic, respectively.

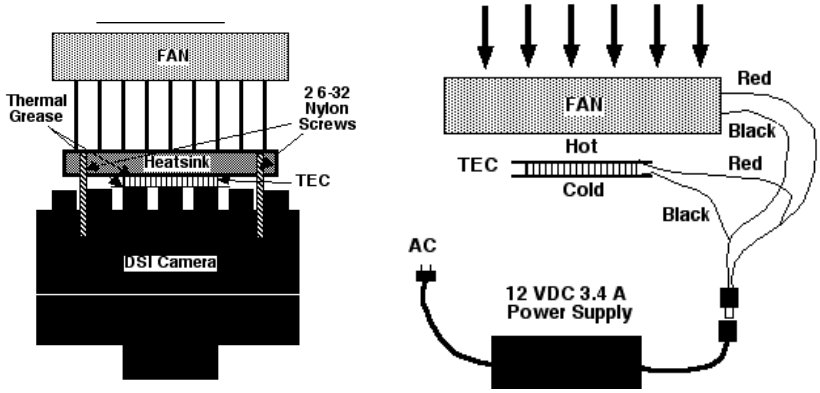

Figure A-8. Mechanical Modification Drawing and Electrical Schematic.

Conclusion

With the addition of BVRI photometric filters and a few simple modifications, the monochrome DSI Pro and DSI Pro-II CCD cameras can be used for serious astronomical photometry. Beware, photometry can be addictive, but very rewarding.

List Of Suppliers for Filters and Cooler Mods

(**Note:** This list is provided for information only.)

Low-Profile Nose Piece TEE Thread Adapter, from **Scope Stuff**:
http://www.scopestuff.com/ss_dsif.htm

ATIK Filter Wheel, from **Adirondack Astro Video**:
http://www.astrovid.com/prod_details.php?pid=2680
ATIK Products web pages:
http://www.telescope-service.com/atik/start/atikstart.html

Schuler BVRI Photometric Filters from **Astrodon**:
http://www.astrodon.com/products/product.cfm?CatID=4
(**Note:** The U band filter is not needed for CCD work.)

TEC Cooler, Heat Sink, and Fan, and other electronic parts from **ALL Electronics**: http://www.allelectronics.com/

Optional Accessories

Outback TEC Cooler (Bolt-on replacement back plate assembly with TEC cooler, heatsink./fan, and temperature controller) from **Steven Mogg** (Australia): http://webcaddy.com.au/Outback

Clip-On 12VDC Fan Accessory Part No. 04531 from
Meade Instruments (See Meade dealers):
http://www.meade.com/dsi/dsi_accessories.html
Series 4000 Focal Reducer Lens from **Meade Instruments**
(See Meade dealers).

Note: All of the modifications described in this Appendix are performed at the sole risk of the owner. No fitness or suitability of use is implied, and may **void the camera warranty**. All consequences are at the sole risk of the owner/installer.

APPENDIX B
Calculating the Air Mass

Introduction

The listed corrected magnitudes of stars are given as they would be seen outside the Earth's atmosphere. These values are the values found in books and tables that list a star's extraterrestrial magnitude.

When starlight passes through the Earth's atmosphere, it is diminished by a variable factor. This attenuation, known as atmospheric extinction, is caused by absorption of some of the starlight by the atmosphere. The greater the thickness of the atmosphere the starlight passes through, the greater the extinction. Observations made at observatories located at high altitude have less extinction than those at a lower altitude. This is one reason why most major observatories are located on mountain tops. Observations made directly overhead at the Zenith have the least extinction for a given location. The extinction increases as a star is viewed further from the Zenith, and is at a maximum at (or below) the horizon. The section of atmosphere that the starlight travels through is known as the Air Mass.

One of the first steps in determining a star's magnitude from measurements taken at the Earth's surface is to know the extinction. The key factor in knowing the extinction is in knowing the star's air mass at the time of the observation.

The following is an explanation of how to determine air mass for a given location, time, and star position. While seemingly simple, there are many pitfalls in determining the air mass.

Getting Started

A star's Air Mass, **X**, is the effective path length of air through which starlight has passed to reach the observer. By definition, **X** = 1.00 at the Zenith (straight overhead) and increases as one observes stars closer to the horizon. Letting **Z** be the angular distance of a star from the Zenith ($0° \leq \mathbf{Z} \leq 90°$), then the simplest relationship is:

$$\mathbf{X = \sec Z}$$

This would be correct if the Earth and its atmosphere were flat. However, the Earth's curvature causes the relationship to overestimate the air mass for large zenith distances. The correct configuration is illustrated in Figure B-1.

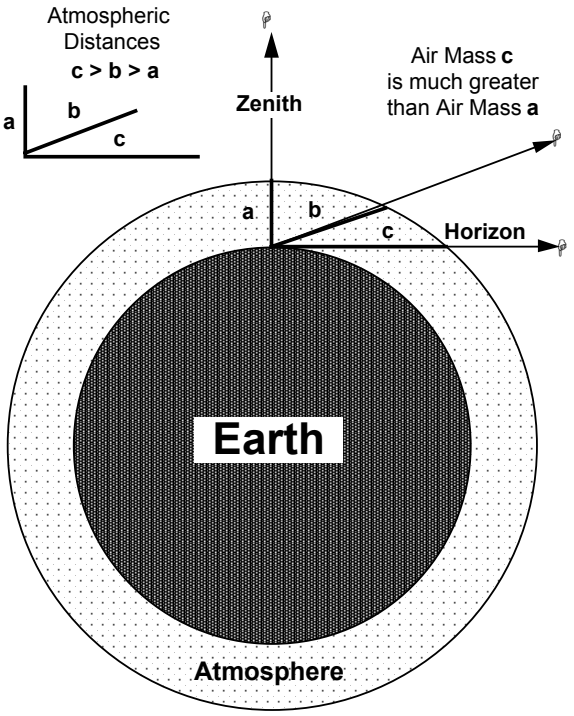

Figure B-1. Illustration of a Star's Air Mass (Accounting for Curvature of the Earth's Atmosphere).

Two equations are in common use that take into account not only the curvature, but also the refraction, of the Earth's atmosphere:

$$\mathbf{X = secZ\,(1 - 0.0012\,(sec^2Z - 1))}$$

$$\mathbf{X = secZ - 0.0018167\,(secZ - 1) - 0.002875\,(secZ - 1)^2 - 0.0008083\,(secZ - 1)^3}$$

Where: The value of **secZ** depends only on the location of the observer and the position of the star in the sky and can be determined by:

$$\mathbf{secZ = (sinLAT\ sin\delta + cos\ LAT\ cos\delta\ cosHA)^{-1}}$$

In this equation , **LAT** is the observer's latitude while **δ** and **HA** are the star's Declination and Hour Angle, respectively. All values are given in decimal degrees.

Note: **Z** in the first equation above refers to the apparent zenith distance of a star (i.e., taking into account atmospheric refraction). In physical terms, this distance is equivalent to the angle between the optical axis of a telescope and a plumb bob hanging from the mounting. However, direct determination of this angle is both cumbersome and inherently inaccurate. In contrast, **Z** in more complex equations refers to the true Zenith Distance, which assumes that no atmospheric refraction is present. Use of the latter value is preferred, as it can be readily calculated from available parameters.

Star's Declination (δ)

As illustrated in Figure B-2, the Declination, **δ**, of a star is the angular distance above or below the celestial equator (which is the projection of the Earth's equator on the celestial sphere). The declination of a star on the celestial equator is 0°, while that of a star at the North Celestial Pole (NCP) would be +90°. Stars between the celestial equator and the NCP have declinations of $0° \leq \delta \leq +90°$.

Similarly, a star situated at the South Celestial Pole (SCP) would have $\delta = -90°$, while those between that pole and the celestial equator have declinations of $-90° \leq \delta \leq 0°$.

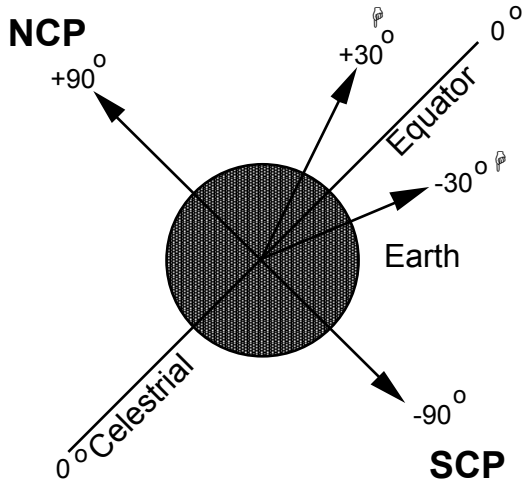

Figure B-2. Illustration of a Star's Declination.

Determining a Star's Hour Angle (HA)

As illustrated in Figure B-3, The observer's celestial meridian is the north-south line passing directly overhead (i.e., through the Zenith). The hour angle, **HA**, of a star is the amount of time since the star crossed the celestial meridian or until the crossing will occur. Stars East of the meridian are designated either as a negative value or with the symbol **E**, while stars to the West have positive values or a symbol **W**. The **HA** of a star increases with time as the celestial sphere rotates.

Mathematically, the Hour Angle is defined as:

HA = (LST – α) hours

Note: **HA** is defined in hours, but must be converted to degrees (angle). To produce this, multiply **HA** in hours by 15 (the sky appears to rotate 15 degrees per hour).

HA = (LST – α) * 15 degrees

Where: **LST** is the local sidereal time and α is the star's Right Ascension. The LST is simply the Right Ascension of a star on the observer's celestial meridian at the time of the observation.

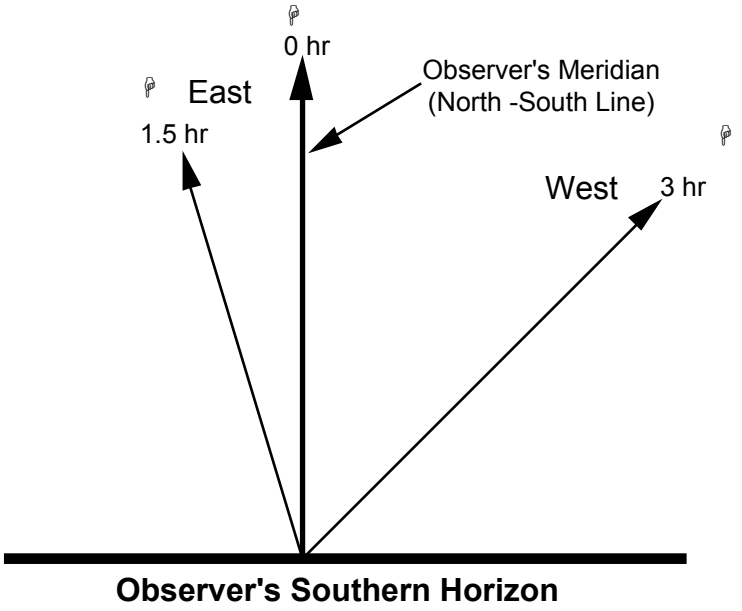

Figure B-3. Illustration of Star's Hour Angle for Northern Hemisphere Observers Facing The Southern Horizon.

Note: The star on the meridian may or may not be the star being observed, and is referred to only to define LST.

Determining Local Sidereal Time (LST)

The LST can be calculated; however high accuracy is needed to determine an accurate LST. Most computers and computer programs have a difficulty in providing sufficient accuracy.

Another approach is to look up the Greenwich Mean Sidereal Time (GMST) from an Astronomical Almanac for UT = 00:00:00 (GMS_{0hUT}), subtract (if West of Greenwich) or add (if East of Greenwich) the observation longitude (in hours) and then add the UT of the observation times the factor 1.00274:

$$\mathbf{LST = (GMS_{0hUT} - Long + 1.00274 * UT)}$$

Where:

GMS_{0hUT} is Greenwich Mean Sidereal Time at UT = 00:00:00.
Long is the Longitude of the observer's site converted from degrees to time from GMT.
UT is the Universal Time of the observation.

The factor 1.00274 is to convert UT solar time to UT sidereal time.

Note: Convert all times to decimal hours:
(Hours + minutes/60 + seconds/3600).

For example:
Kitt Peak National Observatory has a (geodetic) longitude of: –111° 35m 52s or –111.59777778 degrees. This is equivalent to: –7h 26m 23s or 7.423555556 hours West from Greenwich.

Long. (degrees) = 111.597777778 (degrees) * 24/360 (hrs/degree)
Long. (time) = 7.423555556 hours

If an observation was made at 4h 24m 16s (4.406154 hours) UT on 09 September 1990,
GMS_{0hUT} = 23h 11m 52s or 23.18555556 hours
UT = 4.406154 hours

Thus:
LST = 23.18555556 – 7.423555556 + (1.00274 * 4.406154)
LST = 20.180227 hours

Creating an LST Table Using MICA Software

If one is to use a computer program to calculate this, it may be desirable to create a look-up table of all values of LST at UT = 00:00:00 for a ranges of dates. While individual observation UTs can be entered and LST determined, it is not practical to create a table of such times.

It is better to have just one LST per date and location at UT = 00:00:00 and then add or subtract the (UT * 1.00274) to get the LST. This table can be created using the ***U.S. Naval Observatory Multiyear Interactive Computer Almanac (MICA) 1800 - 2050*** program available from Willmann-Bell, Inc. (URL: http://www.willbell.com).

Table B-1 shows a sample list of data from MICA. The date and observation location (a different table is needed for different locations) are specified. The location's LST for that date at UT = 00:00:00 is then looked up. The observation's UT times 1.00274 is then added for each observation time.

Table B-1. Part of a MICA Created Table for LST at HPO (Phoenix, Arizona) for the Month of October 2005.

SIDEREAL TIME

HPO
Location: W112°13'22.0", N33°30'06.0", 200m
(Longitude referred to Greenwich meridian)

Date (UT1)	Time	Greenwich Sidereal Time Mean	Greenwich Sidereal Time App.	Local Sidereal Time Mean	Local Sidereal Time App.	Equation of the Equinoxes
	h m s	h m s	s	h m s	s	s
2005 Oct 01	00:00:00.0	0 39 18.5436	18.2745	17 10 25.0770	24.8079	-0.2691
2005 Oct 02	00:00:00.0	0 43 15.0990	14.8216	17 14 21.6323	21.3550	-0.2774
2005 Oct 03	00:00:00.0	0 47 11.6544	11.3680	17 18 18.1877	17.9013	-0.2864
2005 Oct 04	00:00:00.0	0 51 08.2097	07.9147	17 22 14.7431	14.4480	-0.2950
2005 Oct 05	00:00:00.0	0 55 04.7651	04.4631	17 26 11.2984	10.9965	-0.3020
2005 Oct 06	00:00:00.0	0 59 01.3205	01.0143	17 30 07.8538	07.5476	-0.3062
2005 Oct 07	00:00:00.0	1 02 57.8759	57.5689	17 34 04.4092	04.1022	-0.3069
2005 Oct 08	00:00:00.0	1 06 54.4312	54.1270	17 38 00.9646	00.6603	-0.3042
2005 Oct 09	00:00:00.0	1 10 50.9866	50.6879	17 41 57.5199	57.2212	-0.2987
2005 Oct 10	00:00:00.0	1 14 47.5420	47.2503	17 45 54.0753	53.7836	-0.2917
2005 Oct 11	00:00:00.0	1 18 44.0973	43.8123	17 49 50.6307	50.3456	-0.2850
2005 Oct 12	00:00:00.0	1 22 40.6527	40.3722	17 53 47.1860	46.9055	-0.2805
2005 Oct 13	00:00:00.0	1 26 37.2081	36.9285	17 57 43.7414	43.4619	-0.2795
2005 Oct 14	00:00:00.0	1 30 33.7634	33.4808	18 01 40.2968	40.0141	-0.2826
2005 Oct 15	00:00:00.0	1 34 30.3188	30.0296	18 05 36.8521	36.5629	-0.2892
2005 Oct 16	00:00:00.0	1 38 26.8742	26.5766	18 09 33.4075	33.1099	-0.2976
2005 Oct 17	00:00:00.0	1 42 23.4295	23.1238	18 13 29.9629	29.6572	-0.3057
2005 Oct 18	00:00:00.0	1 46 19.9849	19.6734	18 17 26.5182	26.2067	-0.3115
2005 Oct 19	00:00:00.0	1 50 16.5403	16.2264	18 21 23.0736	22.7597	-0.3139
2005 Oct 20	00:00:00.0	1 54 13.0956	12.7829	18 25 19.6290	19.3162	-0.3128
2005 Oct 21	00:00:00.0	1 58 09.6510	09.3422	18 29 16.1843	15.8755	-0.3088
2005 Oct 22	00:00:00.0	2 02 06.2064	05.9031	18 33 12.7397	12.4364	-0.3033

LST Example

For 21 October 2005 at UT = 07h 10m 00s or 7.166667 hours.

Using the MICA printout shown in Table B-1, the Local Mean Sidereal Time for 21 October 2005 for HPO (Phoenix , Arizona) at Longitude = 112° 13m 22.0s West and Latitude 33° 30m 06.0s North is 18h 29m 16.1843s or 18.487829 hours.

LST = 18.4897829 + 1.00274 * 7.1666667
LST = 25.674132 hours

Note: To test and adjust LST:
If (LST Lookup + UT * 1.00274) ≥ 24,
Use: (LST Lookup + UT * 1.00274) - 24
Otherwise, use: LST Lookup + UT * 1.00274.
Since the above value is greater than 24, 24 hours must be subtracted from it to give:

LST = 1.674132 hours

Determining the Hour Angle (HA)

HA = LST – α

To determine the Observation's Hour Angle (**HA**), the observed star's Right Ascension (**α**) is subtracted from the Local Sidereal Time (**LST**).

For example:
Assume star **α Aur:**

RA = α = 5h 16m 41.3s or 5.278139 hours
Dec = δ = 45° 59m 53.0s or 45.998056 degrees

For **LST = 1.674132 hours:**

HA= 1.674132 – 5.278139
HA = –3.604007 hours

To convert **HA** from hours to degrees:

HA = –3.604007 * 15 degrees
HA = –54.060105 degrees

Alternatively, the hour angle of a star can be determined directly from the telescope's right ascension setting circle (if so equipped) by noting the difference in right ascension between the star and the meridian.

Because the celestial equator intersects the observer's horizon at the due east and west points, a star with $\delta = 0°$ (on the celestial equator) is above the horizon for exactly 12 hours; the star rises with HA = –6 hour and sets with HA = +6 hours. For observers in the Earth's northern hemisphere, a star with $\delta < 0°$ spends less than 12 hours above the horizon each day, while a star with $\delta > 0°$ is visible more than 12 hours per day. As a final comment, note that circumpolar stars never rise nor set, so that their hour angle can range from –12 hours (12 hours East) to +12 hours (12 hours West). The hour angle is zero for stars at upper culmination.

Determining the Air Mass

Now that we know the **HA** for the observation, the value of **secZ** and thus the Air Mass, **X,** can be calculated:

$$\mathbf{secZ = (sinLat\ sin\delta + cos\ Lat\ cos\delta\ cosHA)^{-1}}$$

Latitude for HPO (Phoenix, Arizona):

Lat = 33° 30m 06.0s North or +33.50166667 degrees

Declination and Right Ascension for **α Aur:**

δ = +45.998056 degrees

HA = –54.060105 degrees

Thus:

$$\mathbf{secZ = 1.4061942273781}$$

To determine Air Mass, **X**:

$$\mathbf{X = secZ - 0.0018167\ (secZ - 1) - 0.002875\ (secZ - 1)^2 - 0.0008083\ (secZ - 1)^3}$$

$$\mathbf{X = 1.404928}$$

An example of a FileMaker Pro program printout used at HPO for calculating Air Mass is shown in Figure B-4.

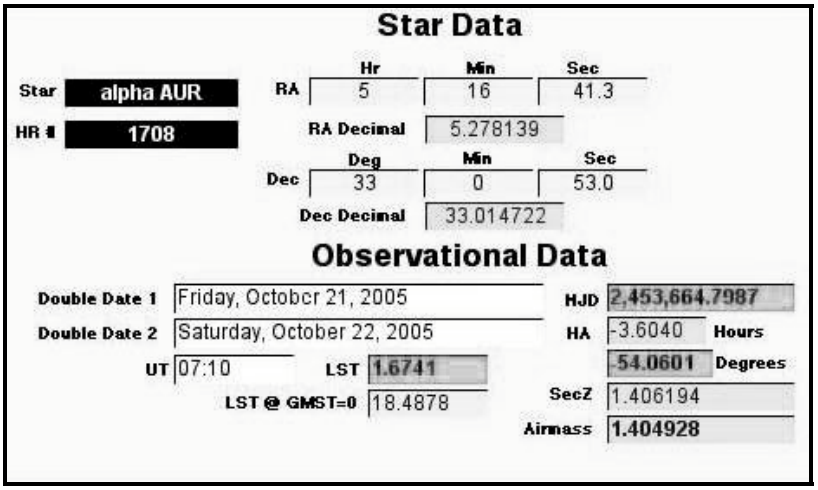

Figure B-4. HPO FileMaker Pro Program for Calculating Air Mass.

Appendix C
Determining Standard Star Data

Observing Standard Stars in M67 (NGC2682)

To determine color transformation coefficients, the first thing that must be done is to image some standard stars whose BVRI magnitudes are known. During the winter and spring, the open cluster M67 (NGC 2682) provides a good grouping for this purpose. It is best to plan your observing session so that you can observe M67 twice over a long time period during the evening.

One observation should be with M67 far from the meridian, either before or after the meridian crossing; and one observation with M67 close to or on the meridian. For best results several images should be taken spaced somewhat evenly between the first and last observation. Precise spacing is not needed, however. These observations will provide data over a large air mass range for determining the atmospheric extinction.

The observation at or close to the meridian will also be the one used for the color transformation coefficient determination. This is because there is always an error in the extinction determination, and extinction effects are minimized close to the meridian.

For wintertime observations, it is usually best to get an image early in the evening to the East and then one on the meridian. Later in the springtime, you will need to take the first one close to the meridian and the second one further West. Ideally, the Air Mass difference should at least 1.5.

Be watchful for clouds, hazeness, or fog that can upset the readings. The night should be clear. The Moon will not present a problem, unless it is close to M67. Since the sky background is subtracted from the star + sky data, a bright sky is compensated for.

Figure C-1 shows a wide field view of M67, from the First Palomar Sky Survey (POSS I). (Ref: R. Miles, *JBAA* **108** p. 65, 1998.) The smaller rectangle near the bottom is where the stars of interest lie.

The epoch 2000 coordinates for star cluster M67 (NGC 2682) are:
RA = 08h 51m 21s , and Dec = +11d 46m 18s.
The epoch 2000 coordinates for the area of interest in M67 are:
RA = 08h 51m 44s, and Dec = +11d 46m 32s.

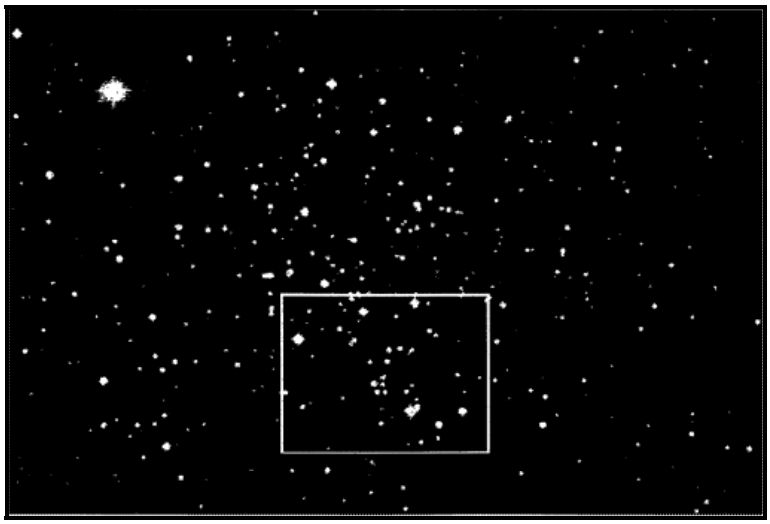

Figure C-1. M67 Open Cluster Photograph.

Figure C-2 is a composite of ten 4-second exposures using a B filter and a modified DSI Pro CCD camera on a 12 inch (30.5 cm) LX200 GPS telescope at HPO.

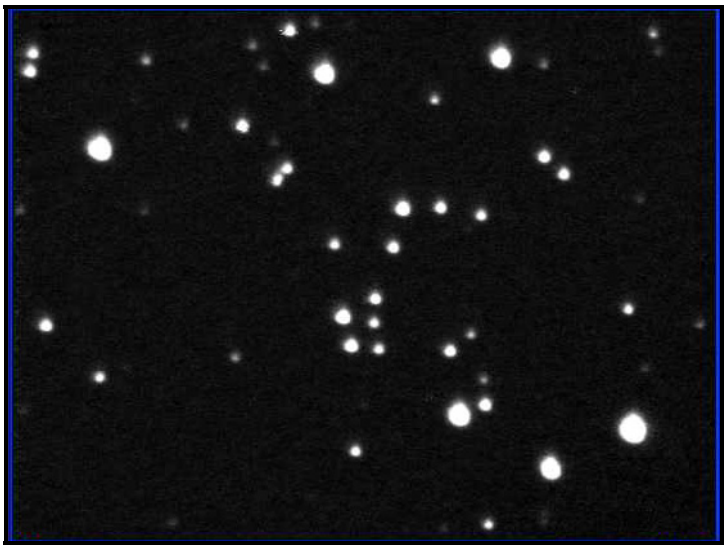

Figure C-2. M67 CCD Image Taken at HPO.

Table C-1 shows sample raw ADU Total Flux counts for the standard stars in M67. These data were taken with 15-second exposures in each filter (sky counts have been subtracted by the software).

Table C-1. Sample Raw ADU Total Flux Data from M67.

	Filter			
Star ID	**B**	**V**	**R**	**I**
M67-081	418581.7	672151.8	550120.0	183962.9
M67-108	162246.7	816575.1	1321557.5	839716.2
M67-117	16926.3	816575.1	66663.2	33397.6
M67-124	32157.9	80115.8	83593.1	35806.7
M67-127	7160.0	43625.1	50523.8	22592.5
M67-130	16492.3	42037.1	44009.5	18563.3
M67-134	27774.8	73617.1	84096.3	39921.9
M67-135	38165.5	154767.1	212966.4	117236.9

Figure C-3 shows the star locations used in M67. Use the identified stars along with Table C-2 for their standard magnitudes.

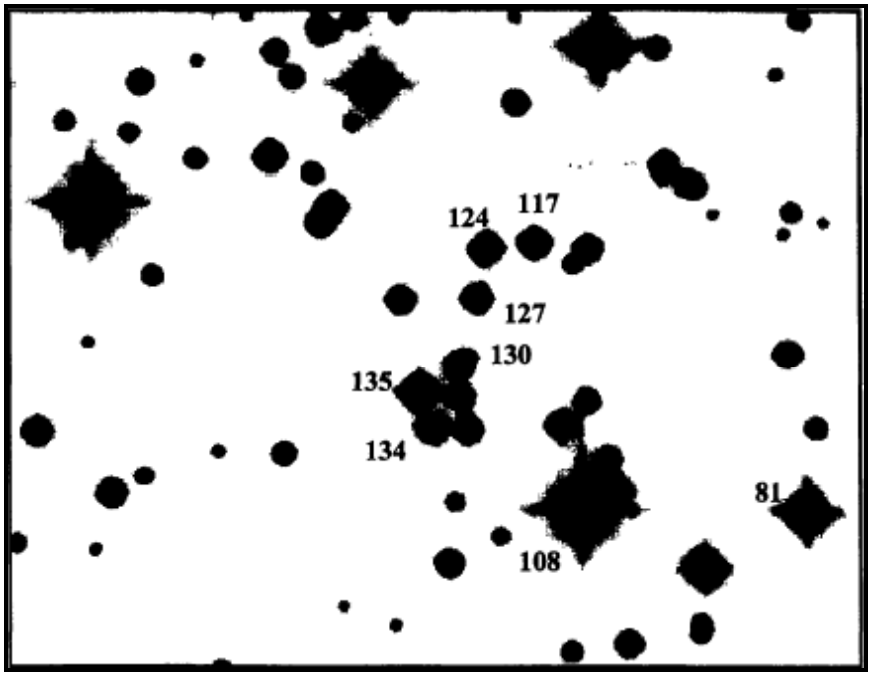

Figure C-3. M67 Finder Chart for Star Identifications.

BVRI Standard Magnitudes in M67

Table C-2 lists the BVRI standard magnitudes of the stars in M67 to be used for the calibration.

Table C-2. M67 BVRI Standard Magnitudes.

Star	B	V	B–V	R	V–R	I	R–I	V–I
081	9.944	10.024	–0.080	10.064	–0.040	10.092	–0.028	–0.068
108	11.081	9.711	1.370	10.064	0.707	8.360	0.644	1.351
117	13.409	12.625	0.784	12.159	0.466	11.721	0.438	0.904
124	12.576	12.119	0.457	11.839	0.280	11.561	0.278	0.558
127	13.328	12.776	0.552	12.454	0.322	12.126	0.328	0.650
130	13.342	12.894	0.448	12.611	0.283	12.319	0.292	0.575
134	12.842	12.262	0.580	11.928	0.334	11.603	0.325	0.659
135	12.505	11.445	1.060	10.889	0.556	10.390	0.499	1.055

APPENDIX D
Determining BVRI Extinction Coefficients

Introduction

Different photometric equipment and telescope combinations can produce different responses to the same star. For accurate data and data that can be combined with that taken by other observers with other equipment, it is important to use a calibrated photometric system. This means knowing the **color transformation coefficients** of the system for the equipment. Since most CCD photometry utilizes images of the Program and Comparison star taken in the same field, and thus close together, the extinction cancels when doing differential photometry. However, to determine color transformation coefficients the extinction coefficients must be known exactly, even for CCD photometry of the same field. Determination of the atmospheric extinction coefficients can be done during the same night that the color transformation coefficients are determined. The secret is to make several observations over a fairly wide range of air masses.

Appendix C gives information on observing the star cluster M67 for standard star data. For the extinction determination, only one star's data needs to be used. In this case, the star labeled 081 in M67 is used. The reason is that the color magnitudes for this star (B–V), (I–R), and (V–I) are close to zero, and thus will minimize any errors.

Air Mass

As explained in Appendix B, the Air Mass is the amount of atmosphere that the star light has traveled through. Air Mass is a function of the angle between the star and the Zenith (straight overhead). Computing the air mass value is a complex process, as described in detail in Appendix B. The Air Mass must be known when determining both the extinction and color transformation coefficients.

Terms and Definitions

It is very important to define terms and keep them straight. The following is a list of definitions used in the equations for extinction determination.

Measured Data (Standard Star)

I Star Counts	**V Star Counts**
R Star Counts	**B Star Counts**

Calculated Data (Corrected for 1.0 second integration time)

I Star Counts Corrected	**V Star Counts Corrected**
R Star Counts Corrected	**B Star Counts Corrected**

Equations

Magnitudes are first calculated on the instrumental scale, then converted to the natural system, and finally transformed to magnitudes on the standard system.

Instrumental Magnitude Calculations

$i = -2.5 * \log_{10}$ (I Star Counts) **$v = -2.5 * \log_{10}$ (V Star Counts)**

$r = -2.5 * \log_{10}$ (R Star Counts) **$b = -2.5 * \log_{10}$ (B Star Counts)**

Where:

i = Instrumental I Magnitude	**v = Instrumental V Magnitude**
r = instrumental R Magnitude	**b = Instrumental B Magnitude**

The I, R, V, and B Star Counts are normalized to counts per second. The basic equations for removing the atmospheric effects on the data are:

$$i_o = i - k'_i * X$$
$$v_o = v - k'_v * X$$
$$r_o = r - k'_r * X$$
$$b_o = b - k'_b * X$$
$$k'_{vi} = k'_v - k'_i$$
$$k'_v = k'_v$$
$$k'_{vr} = k'_v - k'_i$$
$$k'_{bv} = k'_b - k'_v$$
$$k'_{ri} = k'_r - k'_i$$

Where:

i_o, r_o, v_o, and i_o are magnitudes corrected for extinction

k'_{vi} = (v–i) Extinction Coefficient

k'_{v} = (v) Extinction Coefficient

k'_{vr} = (v–r) Extinction Coefficient

k'_{bv} = (b–v) Extinction Coefficient

k'_{ri} = (r–i) Extinction Coefficient

X = Air Mass for the observation

The **BVRI** system defined here uses one simple magnitude, **V**, and four simple color indices, **(V – I), (V – R), (R – I),** and **(B – V)**. In some texts, the system is defined not only in these terms but also by an alternative set consisting of the four simple magnitudes, **B**, **V**, **R,** and **I**.

Note: (V – I) is used in the following equations, but actually is not necessary as final values for **(V – I)** can be determined from the **(V – R)** and **(R – I)** values.

Determining the Extinction Coefficients

There are three cases for determining extinction coefficients: data used for differential photometry; data when color transformation coefficients are not known; and data when they are known. In each case, the equations are of the form for a straight line:

Y = MX + B

Where: **M** is the slope and is equal to the filter band's extinction coefficient. Because we are only interested in extinction for use in determining the color coefficients, we will just use the first case as it is simpler:

Slope = Δ Magnitude / Δ Air Mass

For this case, a single standard star is used. The star should be observed at varying air masses (**X = 1.0 to 1.5 or greater**). A minimum of four and if possible a dozen or more data point are suggested. We have chosen to use the M67 star cluster to obtain data on stars that have well-determined magnitudes.

One of the suggested stars is labeled M67-081. Tables D-1 and D-2 list the observed counts for M67-081. Note: The following data is used as an example and is not necessarily "real" data.

Table D-1. Example I and R Observational Data for Star M67-081.

I Filter			R Filter		
UT	**X**	**i Counts**	**UT**	**X**	**r Counts**
04:55:15	1.0768	183962	04:50:57	1.0775	550120
04:58:36	1.1055	177526	05:11:16	1.0771	548349
06:15:33	1.1266	172358	06:10:23	1.1195	545120
07:21:39	1.2781	149238	07:16:35	1.2617	535115
08:15:45	1.5278	113238	08:10:40	1.4971	523145

Table D-2. Example V and B Observational Data for Star M67-081.

V Filter			B Filter		
UT	**X**	**v Counts**	**UT**	**X**	**b Counts**
04:46:24	1.0786	672152	04:40:02	1.0809	448582
05:29:26	1.0830	668065	05:33:32	1.0852	446448
06:06:26	1.1145	612053	05:36:29	1.0869	445945
07:12:15	1.2484	552542	07:02:17	1.2203	420435
08:05:45	1.4691	412892	07:59:43	1.4369	385359

Determination of Instrumental Magnitudes

The following equations are for determining the Instrumental Magnitudes. Table D-3 lists the calculated values.

$i = -2.5 * \log_{10}$ (i Star Counts)

$v = -2.5 * \log_{10}$ (v Star Counts)

$r = -2.5 * \log_{10}$ (r Star Counts)

$b = -2.5 * \log_{10}$ (b Star Counts)

Table D-3. Calculated Instrumental Magnitudes.

I Filter			R Filter		
UT	**X**	**i**	**UT**	**X**	**r**
04:55:15	1.0768	–10.2216	04:50:57	1.0775	–11.4109
04:58:36	1.1055	–10.1829	05:11:16	1.0771	–11.4074
06:15:33	1.1266	–10.1509	06:10:23	1.1195	–11.4010
07:21:39	1.2781	–9.9945	07:16:35	1.2617	–11.3809
08:15:45	1.5278	–9.6948	08:10:40	1.4971	–11.3563

V Filter			B Filter		
UT	**X**	**v**	**UT**	**X**	**B**
04:46:24	1.0786	–11.6284	04:40:02	1.0809	–11.1894
05:29:26	1.0830	–11.6218	05:33:32	1.0852	–11.1842
06:06:26	1.1145	–11.5267	05:36:29	1.0869	–11.1830
07:12:15	1.2484	–11.4157	07:02:17	1.2203	–11.1190
08:05:45	1.4691	–11.0994	07:59:43	1.4369	–11.0244

$\mathbf{i_o}$,$\mathbf{r_o}$,$\mathbf{v_o}$, and $\mathbf{b_o}$ are magnitudes corrected for extinction, or the magnitudes as they would be without extinction (i.e., measured outside the Earth's atmosphere).

$$\mathbf{i_o = i - k'_i * X} \qquad \mathbf{b_o = b - k'_b * X}$$
$$\mathbf{r_o = r - k'_r * X} \qquad \mathbf{v_o = v - k'_v * X}$$

Or to put the equations in the form of **Y = MX +B:**

$$\mathbf{i = k'_i * X + i_o} \qquad \mathbf{b = k'_b * X + b_o}$$
$$\mathbf{r = k'_r * X + r_o} \qquad \mathbf{v = k'_v * X + v_o}$$

The data are then plotted for each filter versus the air mass, **X**, as shown in Figures D-1 through D-4.

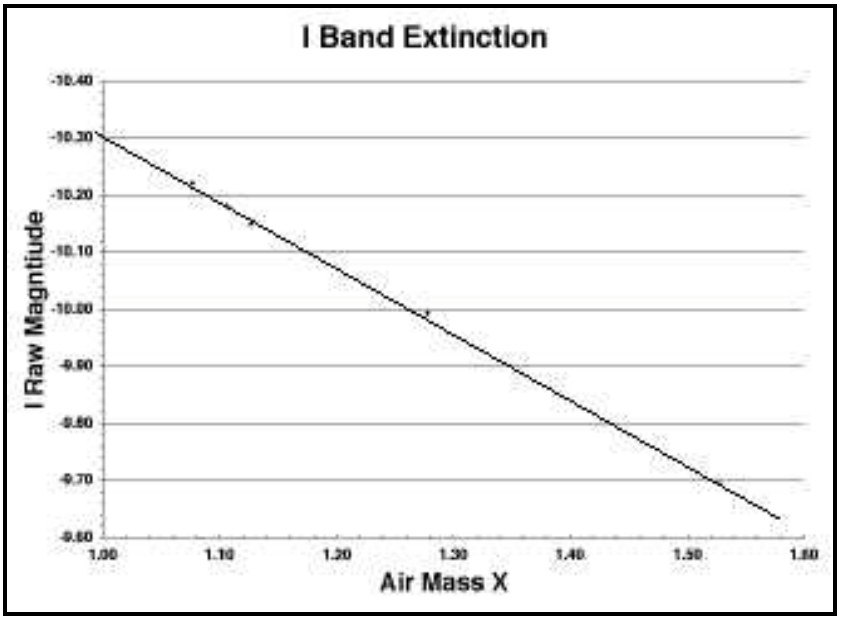

Figure D-1. Plot of i versus X.

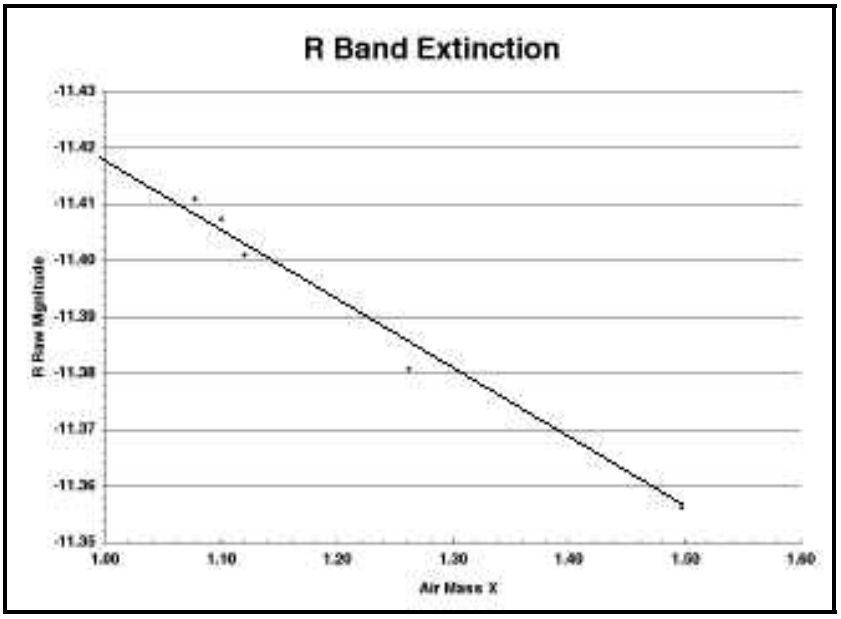

Figure D-2. Plot of r versus X.

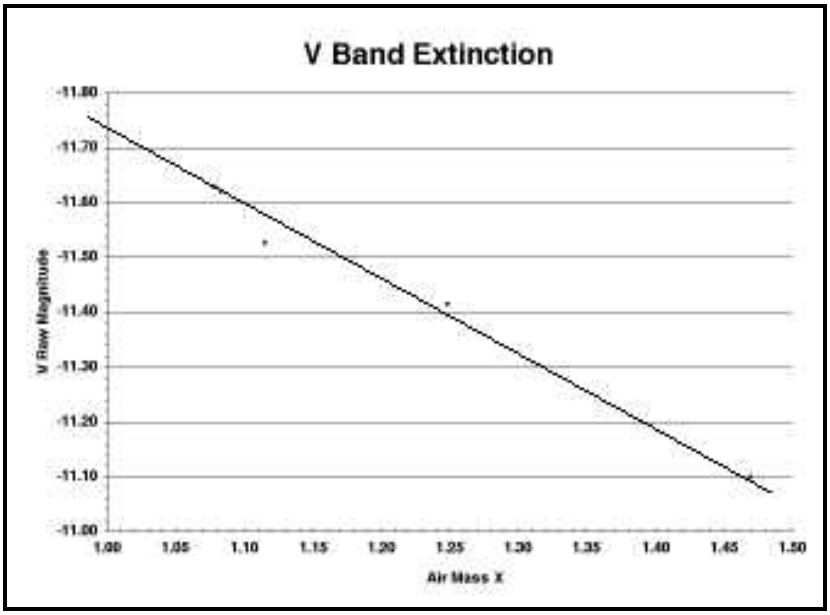

Figure D-3. Plot of v versus X.

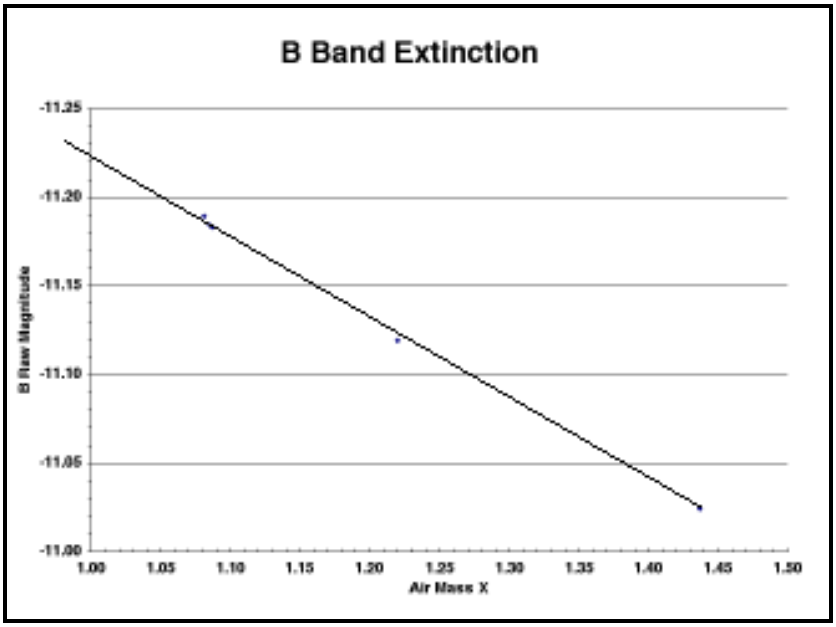

Figure D-4. Plot of b versus X.

The slopes are then determined and are equated to the filter band's extinction coefficient.

Summary of Extinction Determination

Δ i / Δ X = k'_i
0.9000 / 1.5250 = 0.590
k'_i = 0.590

Δ v / Δ X = k'_v
0.6400 / 1.4690 = 0.436
k'_v = 0.436

k'_{vi} = 0.436 – 0.590
k'_{vi} = –0.154

k'_{vr} = 0.436 – 0.549
k'_{vr} = –0.113

Δ r / Δ X = k'_r
0.0615 / 1.500 = 0.041
k'_r = 0.041

Δ b / Δ X = k'_b
0.1880 / 1.1439 = 0.131
k'_b = 0.131

k'_{ri} = 0.041 – 0.590
k'_{ri} = –0.549

$k'b_v$ = 0.131 – 0.436
$k'b_v$ = –0.305

Extinction Coefficients

k'_{vi} = –0.154
k'_{ri} = –0.5.49
k'_v = –0.436

k'_{vr} = –0.113
k'_{bv} = –0.305

APPENDIX E
Determining BVRI Color Coefficients

Introduction

Different photometric equipment and telescope combinations can produce different responses to the same star. For accurate data and data that can be combined with that taken by other observers with other equipment, it is important to use a calibrated photometric system. This means knowing the color transformation coefficients of the system and at least an average set of extinction coefficients for the observatory. In fact, to determine the color transformation coefficients, the extinction coefficients must be known. Determination of the extinction coefficients can be done during the same night that the data for the color transformation coefficients are determined (see Appendix D).

Air Mass

Air Mass is the thickness of the Earth's atmosphere that star light has passed through. The Air Mass value increases as a function of the angle of the star downward from the Zenith (straight overhead). Computing the Air Mass value is complex; this is described in detail in Appendix B. The Air Mass must be known when determining both the atmospheric extinction and color transformation coefficients. To standardize your data, you must determine your system's color transformation coefficients and use those coefficient when reducing the data.

Having determined the extinction coefficients that account for atmospheric effects, the next step is to transform the data to the standard UBVRI system. This is done by observing a set of standard stars with a wide range of known colors, applying the extinction corrections, and then determining the coefficients using the following equations.

Terms and Definitions

Note: (V – I) is used in the following equations, but is actually not necessary, as final values for **(V – I)** can be determined from the **(V – R)** and **(R – I)** values.

Observational Data
I Star Counts = i counts
R Star Counts = r counts
V Star Counts = v counts
B Star Counts = b counts

Calculated Data
(Corrected for 1.0-second integration time)
I Star Count Corrected = i counts
R Star Count Corrected = r counts
V Star Count Corrected = v counts
B Star Count Corrected = b counts

Observational Data

The following data has been modified slightly, but is based on actual data taken at the Hopkins Phoenix Observatory (HPO) with a modified DSI Pro CCD camera, imaging the M67 star cluster (an object with well-determined comparison values). Star counts have been normalized for a 1-second integration time. X is the Air Mass for the observation. Table E-1 lists the raw count data.

Table E-1. Observational Star Counts.

Star ID	X	i counts	r counts	v counts	b counts
M67-081	1.0678	183962.9	550120.0	672151.8	418581.7
M67-108	1.0678	839716.2	1321557.5	816575.1	162246.7
M67-117	1.0678	33397.6	66663.2	52113.7	16926.3
M67-124	1.0678	35806.7	83593.1	80115.8	32157.9
M67-127	1.0678	22592.5	50523.8	43625.1	7160.0
M67-130	1.0678	18563.3	44009.5	42037.1	16492.3
M67-134	1.0678	39921.9	84096.3	73617.1	27774.8
M67-135	1.0678	117236.9	212966.4	154767.1	38165.5

Because of the volume of data involved, it is suggested that a computer program be developed to handle the calculations. As mentioned earlier, FileMaker Pro is an easy-to-learn database program ideally suited to these tasks. Figure E-1 shows a screen shot of a database developed at the Hopkins Phoenix Observatory (HPO).

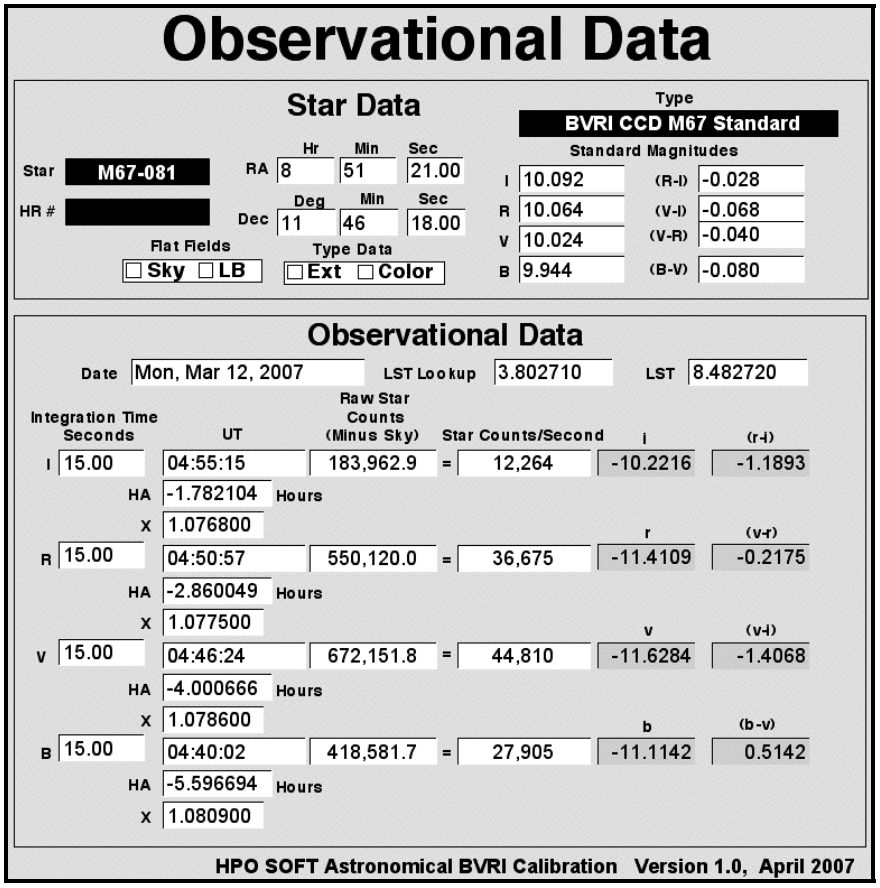

Figure E-1. Example FileMaker Pro Observational Data Calculations.

Figure E-2 shows a screen shot of another part of the FileMaker Pro program used at HPO, illustrating the resulting Transformation Coefficient Calculations, ready to plot.

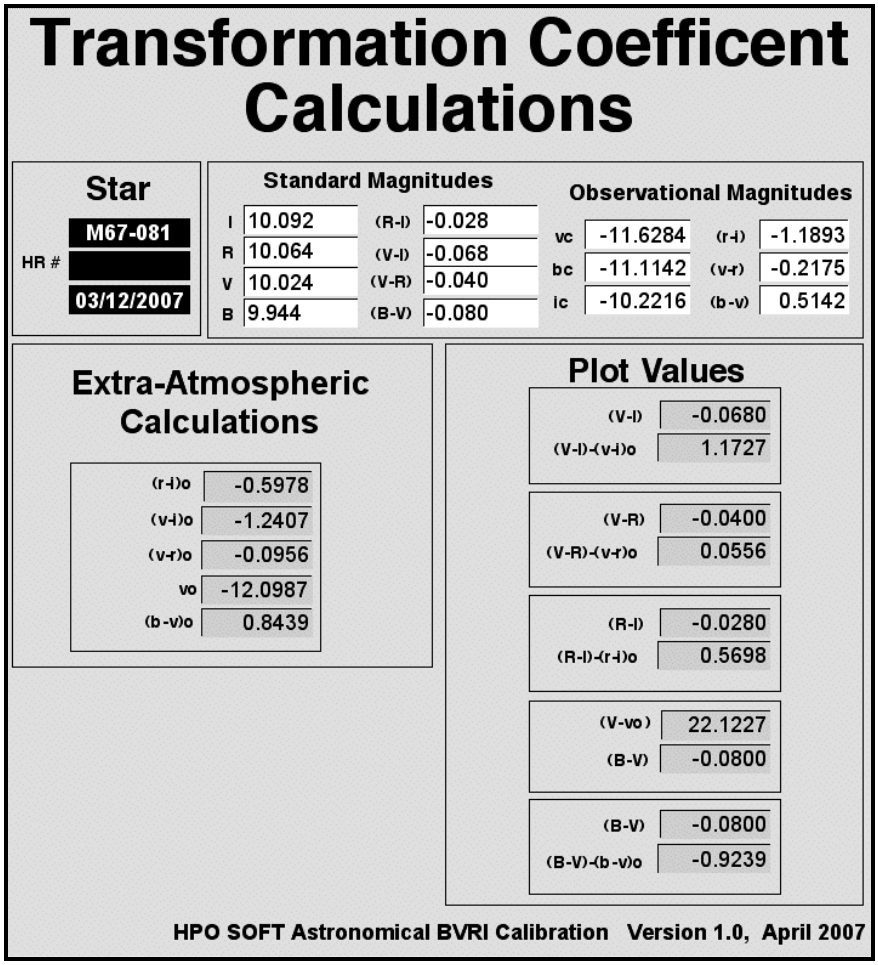

Figure E-2. Example FileMaker Pro Transformation Coefficient Calculation.

Instrumental Magnitude Calculations

Table E-2 lists a summary of the instrumental magnitude calculations.

Table E-2. Instrumental Magnitude Calculations Summary.

Star ID	X	i	r	v	b
M67-081	1.0809	–10.2216	–11.4109	–11.6284	–11.1142
M67-108	1.0809	–11.8701	–12.3625	–11.8398	–10.0852
M67-117	1.0809	–8.3691	–9.1195	–8.8522	–7.6312
M67-124	1.0809	–8.4447	–9.3652	–9.3191	–8.3280
M67-127	1.0809	–7.9447	–8.8185	–8.6591	–7.6461
M67-130	1.0809	–7.7314	–8.6686	–8.6189	–7.6030
M67-134	1.0809	–8.5628	–9.3717	–9.2272	–8.1689
M67-135	1.0809	–9.7324	–10.3805	–10.0340	–8.5139
Note: Filter = $-2.5 * \log_{10}$ (Counts) e.g., i = $-2.5 \log_{10}$ (i counts)					

Extra-Atmospheric Calculations

Table E-3 lists the extra-atmospheric calculations.

Table E-3. Extra-Atmospheric Calculations (X = 1.0809).

Star ID	$(r-i)_0$	$(v-i)_0$	v_0	$(v-r)_0$	$(b-v)_0$
M67-081	–0.5978	–1.2407	–12.0987	–0.0956	0.8439
M67-108	0.0991	0.1964	–12.3100	0.6446	2.0843
M67-117	–0.1589	–0.3170	–9.3225	0.3892	1.5507
M67-124	–0.3290	–0.7083	–9.7894	0.1680	1.3208
M67-127	–0.2823	–0.5483	–9.1294	0.2813	1.3427
M67-130	–0.3456	–0.7214	–9.0892	0.1716	1.3456
M67-134	–0.2174	–0.4983	–9.6975	0.2664	1.3880
M67-135	–0.0566	–0.1355	–10.5043	0.4683	1.8498

Table E-4 lists the basic equations and the extinction values (determined in Appendix D).

Table E-4. Equations and Extinction Values.

Equation	Extinction from Appx. D
$(r–i)_o = (r–i) – k'_{ri} * X$	$k'_{ri} = –0.5490$
$(v–i)_o = (v– i) – k'_{vi} * X$	$k'_{vi} = –0.154$
$(v–r)_o = (v – r) – k'_{vr} * X$	$k'_{vr} = –0.113$
$V_o = v – k'_v * X$	$k'_v = 0.436$
$(b–v)_o = (b – v) – k'_{bv} * X$	$k'_{bv} = –0.305$

Where:

$(r–i)_o$ = **Extra–Atmospheric (r–i) Magnitude**
$(v–i)_o$ = **Extra–Atmospheric (v–i) Magnitude**
$(v–r)_o$ = **Extra–Atmospheric (v–r) Magnitude**
v_o = **Extra–Atmospheric v Magnitude**
$(b–v)_o$ = **Extra–Atmospheric (b–v) Magnitude**
k'_{ri} = **1st Order (R – I) Extinction Coefficient**
k'_v = **1st Order V Extinction Coefficient**
k'_{vi} = **1st Order (V – I) Extinction Coefficient**
k'_{vr} = **1st Order (V – R) Extinction Coefficient**
k'_{bv} = **1st Order (B – V) Extinction Coefficient**

Standard Star Magnitudes

Table E-5 lists the standard star magnitudes.

Table E-5. Standard Star Magnitude Data.

Star ID	V–I	V–R	R–I	V	B–V
M67-081	–0.068	–0.040	–0.028	10.024	–0.080
M67-108	1.351	0.707	0.644	9.711	1.370
M67-117	0.904	0.466	0.438	12.625	0.784
M67-124	0.558	0.280	0.278	12.119	0.457
M67-127	0.650	0.322	0.328	12.776	0.552
M67-130	0.575	0.283	0.282	12.894	0.448
M67-134	0.659	0.334	0.325	12.262	0.580
M67-135	1.055	0.556	0.499	11.445	1.060

Color Transform and Zero Point Calculations

Tables E-6(a), (b), and (c) list the Color Transformation and Zero Point Calculations. These Tables are from a FileMaker Pro database program developed at HPO.

Table E-6(a). (R-I) Color Transformation Plot Calculations.

Star ID	$(R - I) - (r - i)_0$	(R – I)
M67-081	0.5698	–0.0280
M67-108	0.5449	0.6440
M67-117	0.5969	0.4380
M67-124	0.6070	0.2780
M67-127	0.6103	0.3280
M67-130	0.6377	0.2920
M67-134	0.5424	0.3250
M67-135	0.5556	0.4990

Table E-6(b). (V-I) and (V-R) Color Transformation Plot Calculations.

Star ID	$(V - I) - (v - i)_0$	(V – I)	$(V - R) - (v - r)_0$	(V – R)
M67-081	1.1727	–0.0680	0.0556	–0.0400
M67-108	1.1546	1.3510	0.0624	0.7070
M67-117	1.2210	0.9040	0.0768	0.4660
M67-124	1.2663	0.5580	0.1120	0.2800
M67-127	1.1983	0.6500	0.0407	0.3220
M67-130	1.2964	0.5750	0.1114	0.2830
M67-134	1.1573	0.6590	0.0676	0.3340
M67-135	1.1905	1.0550	0.0876	0.5560

Table E-6(c). (V) and (B-V) Color Transformation Plot Calculations.

Star ID	$(V - v_0)$	(B – V)	$(B - V) - (b - v)_0$	(B – V)
M67-081	22.1227	–0.0800	–0.9239	–0.0800
M67-108	22.0211	1.3700	–0.7143	1.3700
M67-117	21.9475	0.7840	–0.7667	0.7840
M67-124	21.9084	0.4570	–0.8638	0.4570
M67-127	21.9054	0.5520	–0.7907	0.5520
M67-130	21.9832	0.5480	–0.8976	0.5480
M67-134	21.9595	0.5800	–0.8080	0.5800
M67-135	21.9493	1.0600	–0.7898	1.0600

Color Transform Coefficient Equations

$$((V - I) - (v - i)_o) = (1 - 1 / \alpha) * (V - I) + \zeta_{vi} / \alpha$$
$$((V - R) - (v - r)_o) = (1 - 1 / \beta) * (V - R) + \zeta_{vr} / \beta$$
$$((R - I) - (r - i)_o) = (1 - 1 / \gamma) * (R - I) + \zeta_{ri} / \gamma$$
$$(V - v_o) = \varepsilon * (B - V) + \zeta_v$$
$$((B - V) - (b - v)_o) = (1 - 1 / \mu) * (B - V) + \zeta_{bv} / \mu$$

Where:

α is (V–I) Transformation Coefficient
β is (V–R) transformation Coefficient
γ is (R–I) transformation Coefficient
ε is V Transformation Coefficient
μ is (B–V) Transformation Coefficient

ζ_{vi} is (V–I) Zero Point
ζ_v is V Zero Point
ζ_{ri} is (R–I) Zero Point
ζ_{bv} is (B–V) Zero Point
ζ_{vr} is (V–R) Zero Point

Note: While the color transformation coefficients for **V** and **(B–V)** are generally denoted by ε and μ, respectively, there does not seem to be any standard for the **R** and **I** color transformation coefficients. In this Appendix, the Greek letters α, β, and γ have been assigned for the **(V–I)**, **(V–R),** and **(R–I)** color transformation coefficients, respectively. These equations are in the form of the equation for a straight line: **Y = MX + B**, where **M** is the slope and **B** is the **Y** intercept.

Coefficient Determination

Determining α and ζ_{vi}

A plot of $\mathbf{((V - I) - (v - i)_O)}$ versus $\mathbf{(V - I)}$ has the slope $\mathbf{(1 - 1 / \alpha)}$ and intercept ζ_{vi} / α, from which the values for α and ζ_{vi} can be calculated. This may seem like a strange technique to find the coefficients, but it maximizes accuracy and makes the independent variable a known standard value. The slope $\mathbf{(1 - 1 / \alpha)}$ has a value near zero and can be determined more accurately than the simple slope α.

Table E-7 lists the data and Figure E-3 shows a plot of the data.
The equations are in the form of an equation for a straight line:
$\mathbf{((V - I) - (v - i)_O) = (1 - 1 / \alpha) * (V - I) + \zeta_{vi} / \alpha}$

Table E-7. $((V - I) - (v - i)_O)$ versus $(V - I)$ Data.

$(V-I) - (v - i)_0$	$(V - I)$
1.1727	**-0.0680**
1.1546	**1.3510**
1.2210	**0.9040**
1.2663	**0.5580**
1.1983	**0.6500**
1.2964	**0.5750**
1.1573	**0.6590**
1.1905	**1.0550**

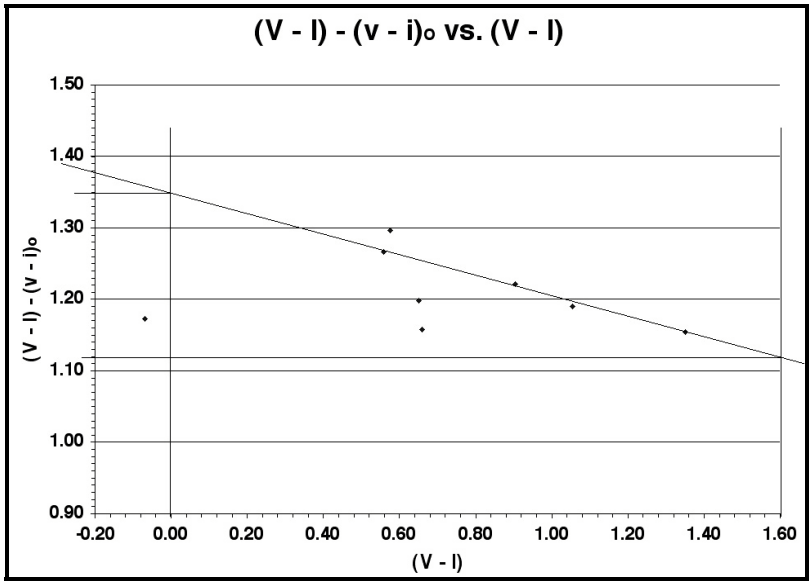

Figure E-3. $((V - I) - (v - i)_o)$ versus (V– I) Plot.

Slope = $(1 - 1 / \alpha)$
$(1 - 1 / \alpha) = [\Delta((V - I) - (v - i)_o)) / \Delta(V - I)]$
$\Delta((V - I) - (v - i)_o)) / \Delta(V - I) = -0.260 / 1.800$
$(1 - 1 / \alpha) = -0.1444$
$\alpha = 1 / (1 - (- 0.1444))$
$\alpha = 0.8738$
α is (V – I) Color Coefficient

Y-Intercept when MX = 0 is ζ_{vi} / α.
Y-Intercept = ζ_{vi} / α
$\zeta_{vi} = \alpha * $ Y-Intercept
$\zeta_{vi} = 1.3400 * 0.8838$
$\zeta_{vi} = 1.1843$
ζ_{vi} is (V – I) Zero Point

Determining β and ζ_{vr}

A plot of $\mathbf{((V - R) - (v - r)_O)}$ versus $\mathbf{(V - R)}$ has the slope $\mathbf{(1 - 1 / \beta)}$ and intercept ζ_{vr} / β, from which the values for β and ζ_{vr} can be calculated. The slope $\mathbf{(1 - 1 / \beta)}$ has a value near zero and can be determined more accurately than the simple slope β.

Table E-8 lists the data and Figure E-4 shows a plot of the data.
The equations are in the form of an equation for a straight line:
$\mathbf{((V–R) – (v–r)_O) = (1–1/\beta) * (V – R) + \zeta_{vr} /\beta}$

Table E-8. $((V – R) – (v – r)_O)$ versus (V – R) Data.

$(V–R) – (v – r)_0$	(V – R)
0.0556	-0.0400
0.0624	0.7070
0.0768	0.4660
0.1120	0.2800
0.0407	0.3220
0.1114	0.2830
0.0676	0.3340
0.0876	0.5560

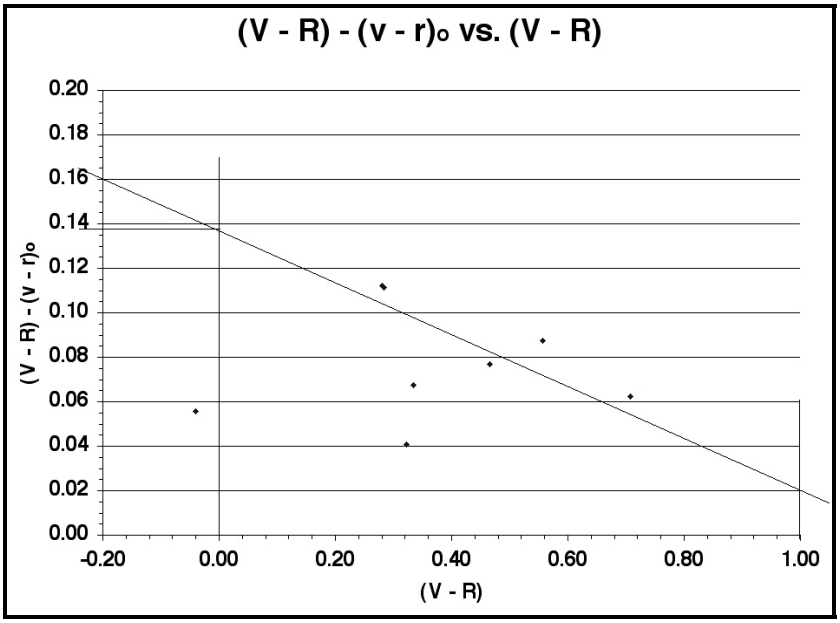

Figure E-4. $((V - R) - (v - r)_o)$ versus $(V - R)$ Plot.

Slope = $(1 - 1 / \beta)$
$(1 - 1 / \beta) = [\Delta((V - R) - (v - r)_o)) / \Delta(V - R)]$
$\Delta ((V - R) - (v - r)_o)) / \Delta (V - R) =$ –
0.1400/1.200
$(1 - 1 / \beta) = -0.1167$
$\beta = 1 / (1 - (-0.1167))$
$\beta = 0.8955$
β is (V – R) Color Coefficient

Y-Intercept when MX = 0 is ζ_{vr} / β
Y-Intercept = ζ_{vr} / β
$\zeta_{vr} = \beta$ * Y-Intercept
$\zeta_{vr} = 0.1375 * 0.8955$
$\zeta_{vr} = 0.1231$
ζ_{vr} is (V– R) Zero Point

Determining γ and ζ_{ri}

A plot of $\mathbf{((R - I) - (r - i)_O)}$ versus $\mathbf{(R - I)}$ has the slope $\mathbf{(1 - 1 / \gamma)}$ and intercept ζ_{ri} / γ, from which the values for γ and ζ_{ri} can be calculated. The slope $\mathbf{(1 - 1 / \gamma)}$ has a value near zero and can be determined more accurately than the simple slope γ.

Table E-9 lists the data and Figure E-5 shows a plot of the data.
The equations are in the form of an equation for a straight line:
$\mathbf{((R - I) - (r - i)_O) = (1 - 1 / \gamma) * (R - I) + \zeta_{ri} / \gamma}$.

Table E-9. ((R - I) - (r - i)$_O$) versus (R - I) Data.

(R–I) – (r – i)$_0$	(R – I)
0.5698	–0.0280
0.5449	0.6440
0.5969	0.4380
0.6070	0.2780
0.6103	0.3280
0.6377	0.2920
0.5424	0.3250
0.5556	0.4990

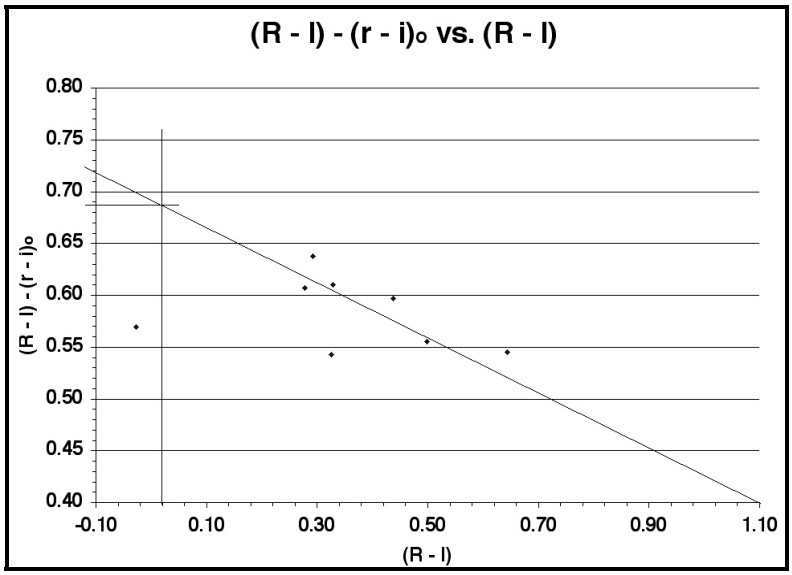

Figure E-5. ((R–I) – (r–i)$_O$) versus (R–I) Plot.

Slope = 1 – 1 / γ)
(1 – 1 / γ) = [Δ((R – I) – (r– i)$_o$)) / Δ(R – I)]
Δ((R – I) – (r– i)$_o$)) / Δ(R – I) = –0.3200/1.2000
(1 – 1 / γ) = –0.2667
γ = 1 / (1 – 0.2667)
γ = 0.7895
γ is (R – I) Color Coefficient

Y-Intercept when MX = 0 is ζ_{ri} / γ
Y-Intercept = ζ_{ri} / γ
ζ_{ri} = γ * Y–Intercept
ζ_{ri} = 0.6860 * 0.7895 = 0.5416
ζ_{ri} = 0.5416
ζ_{ri} is (R – I) Zero Point

Determining ε and ζ_V

Plotting **(V – v$_o$)** versus **(B – V**) produces the slope which is **ε** and the Y–intercept ζ_V.

Table E-10 lists the data and Figure E-6 shows a plot of the data. The equations are in the form of an equation for a straight line: **(V – v$_o$) = ε * (B – V) + ζ_V**

Table E-10. (V – v$_o$) versus ε * (B – V) Data.

(V – v$_o$)	(B – V)
22.1227	–0.0800
22.0211	1.3700
21.9475	0.7840
21.9084	0.4570
21.9054	0.5520
21.9832	0.4480
21.9595	0.5800
21.9493	1.0600

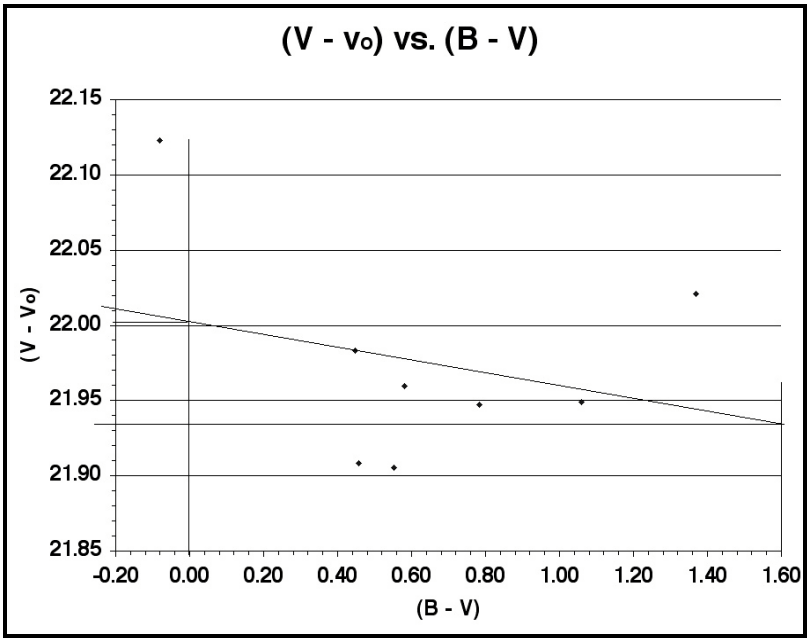

Figure E-6. $(V - v_O)$ versus ε * (B – V) Plot.

Slope = ε

$\varepsilon = \Delta(V - v)_O / \Delta(B - V)$

$\Delta(V - v)_O / \Delta(B - V) = -0.076/1.800$

$\varepsilon = -0.0422$

ε is V Band Color Coefficient

Y-Intercept when MX = 0 is ζ_V

Y-Intercept = ζ_V

$\zeta_V = 22.0085$

ζ_V is V Zero Point

Determining μ and ζ_{bv}

A plot of $\mathbf{((B - V) - (b - v)_o)}$ versus $\mathbf{(B - V)}$ has the slope $\mathbf{(1 - 1 / \mu)}$ and intercept ζ_{bv} / μ, from which the values for μ and ζ_{bv} can be calculated. The slope $\mathbf{(1 - 1 / \mu)}$ has a value near zero and can be determined more accurately than the simple slope μ.

Table E-11 lists the data and Figure E-7 shows a plot of the data. The equations are in the form of an equation for a straight line: $\mathbf{((B - V) - (b - v)_o) = (1 - 1/\mu) * (B - V) + \zeta_{bv} /\mu}$

Table E-11. $((B - V) - (b - v)_o)$ versus $(B - V)$ Data.

$(B - V) - (b - v)_o$	$(B - V)$
-0.9239	**-0.0800**
-0.7143	**1.3700**
-0.7667	**0.7840**
-0.8638	**0.4570**
-0.7907	**0.5520**
-0.8976	**0.4480**
-0.8080	**0.5800**
-0.7898	**1.0600**

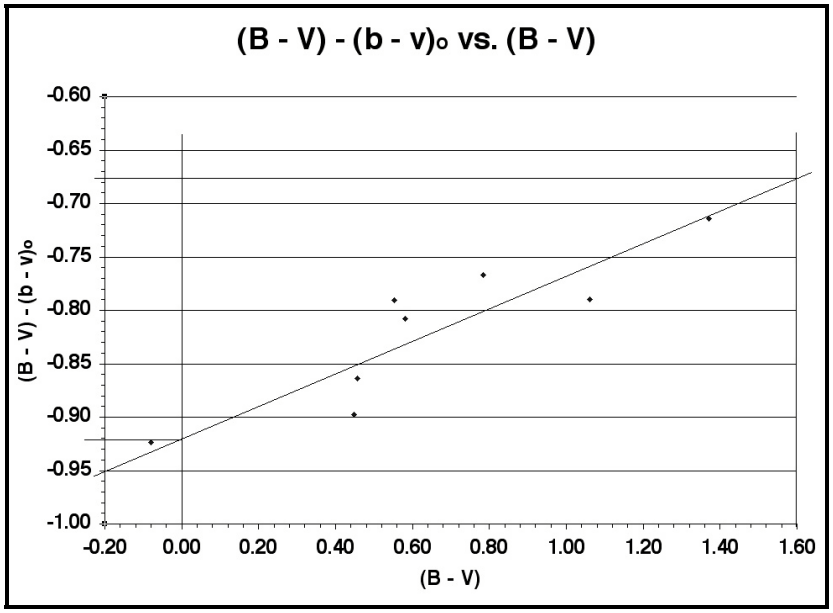

Figure E-7. $((B - V) - (b - v)_o)$ versus (B – V) Plot.

Slope = (1 – 1 / μ)
$(1 - 1 / \mu) = [\Delta((B - V) - (b - v)_o)) / \Delta(B - V)]$
$\Delta((B - V) - (b - v)_o)) / \Delta(B - V) = 0.275/1.800 = 0.1528$
$(1 - 1 / \mu) = 0.1528$
$\mu = 1 / (1 - 0.1528)$
$\mu = 1.1803$
μ is (B – V) Color Coefficient

Y-Intercept when MX = 0 is ζ_{bv} / μ
Y-Intercept = ζ_{bv} / μ
$\zeta_{bv} = \mu *$ Y – Intercept
$\zeta_{bv} = -0.9210 * 1.0871$
$\zeta_{bv} = -1.0012$
ζ_{bv} is (B – V) Zero Point

Summary

Table E-12 gives a summary of the BVRI Color Transformation Coefficients, and Table E-13 summarizes the BVRI Zero Points.

Table E-12. BVRI Color Transformation Coefficients.

$(1 - 1 / \alpha)$	$(1 - 1 / \beta)$	$(1 - 1 / \gamma)$	ε	$(1 - 1 / \mu)$
-0.1444	**-0.1167**	**-0.2667**	**0.0422**	**0.1528**

α	β	γ	ε	μ
0.8738	**0.8955**	**0.7895**	**0.0422**	**1.8030**

Table E-13. BVRI Zero Points.

ζ_{vi} / α	ζ_{vr} / β	ζ_{ri} / γ	ζ_{v}	ζ_{bv} / μ
1.2400	**1.3750**	**0.6860**	**22.0085**	**-0.09210**

ζ_{vi}	ζ_{vr}	ζ_{ri}	ζ_{v}	ζ bv
1.21843	**0.1231**	**0.5416**	**22.0085**	**-1.0012**

APPENDIX F
Least Squares Method

Introduction

While it is possible to graphically plot data for extinction and color transformation coefficient determination, sometimes it is difficult to decide exactly where to draw the straight line plot. By using the method of least squares or linear regression analysis, one can mathematically determine the slope and Y-intercept of data that are in the form of a straight line without having to make a graph and physically draw a line between points.

While the results can be calculated by hand, a calculator or computer program can speed the calculations and provide more accurate results.

Equations

There are basically two equations used, one for the **Slope, b** and one for the **Y-intercept, a**.

$$\textbf{Slope } b = \frac{N * \Sigma (x_i * y_i) - \Sigma x_i * \Sigma y_i}{N * \Sigma x_i^2 - (\Sigma x_i)^2}$$

$$\textbf{Y-Intercept } a = y_{iavg} - b * x_{iavg}$$

Where:

Data points are x_i and y_i.

The variables x_{iavg} and y_{iavg} are the average vales for the x_i and y_i data, respectively.

The sigma (Σ) symbol means the sum.

Table F-1 lists sample data to demonstrate a least squares fit.

Table F-1. Sample Data.

N	Data x_i	x_i^2	Data y_i	$(x_i * y_i)$
1	1.0	1.00	0.47	0.470
2	1.1	1.21	0.43	0.473
3	1.2	1.44	0.39	0.468
4	1.3	1.69	0.36	0.468
5	1.4	1.96	0.33	0.462
6	1.5	2.25	0.29	0.435
7	1.6	2.56	0.25	0.400
8	1.7	2.89	0.21	0.357
9	1.8	3.24	0.16	0.288
10	1.9	3.61	0.15	0.285
11	2.0	4.00	0.12	0.240
N = 11	Σx_i = 16.5	Σx_i^2 = 25.85	Σy_i = 3.16	$\Sigma (x_i * y_i)$ = 4.346

Calculations:

$(\Sigma x_i)^2 = 272.25$

$N = 11$

$\Sigma x_i = 16.5$

$x_{iavg} = \Sigma x_i / N = 16.5 / 11 = 1.5000$

$\Sigma y_i = 3.16$

$y_{iavg} = \Sigma y_i / N = 3.16 / 11 = 0.2873$

$\Sigma (x_i * y_i) = 4.346$

$\Sigma x_i^2 = 25.85$

$(\Sigma x_i)^2 = 272.25$

Slope:

$b = [(11 * 4.346) – (16.5 * 3.16)] / [(11 * 25.85) – 272.25]$

$b = (47.806 – 52.140) / 12.10$

$b = –4.334 / 12.10 = –0.3582$

Y-Intercept:

$a = 0.2873 + (0.3582 * 1.5000) = 0.8246$

Plotting a Graph and Drawing the Straight Line

Figure F–1 shows a manually-plotted line used to determine the slope (b) and Y–intercept (a) values.

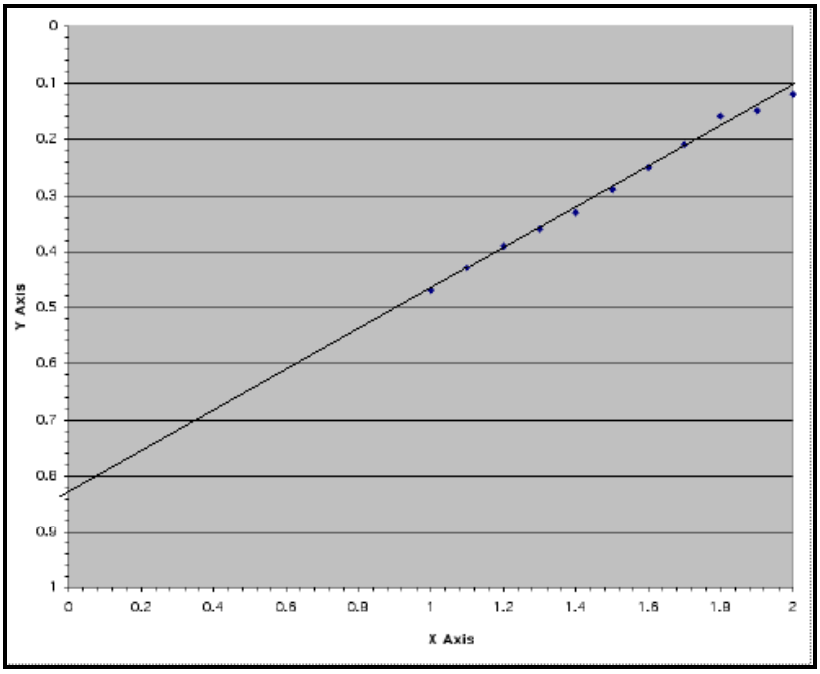

Figure F–1. Manual Data Plot.

From the Graph:

Slope: b = ΔY / ΔX = –0.725 / 2 = –0.3625

ΔY / ΔX means the change (delta) in **Y** divided by the change in **X.**

Y-Intercept: a = 0.825

NOTES

APPENDIX G
FITS Header

Introduction

Images saved as FITS images (.fts files) will have a header automatically created. This header contains useful information about the image.

FITS stands for **Flexible Image Transport System**.

Image Information

To view an image's FITS header, open the image and from the **Tools** pull–down menu select **Image Information**. (Fig. G-1.)

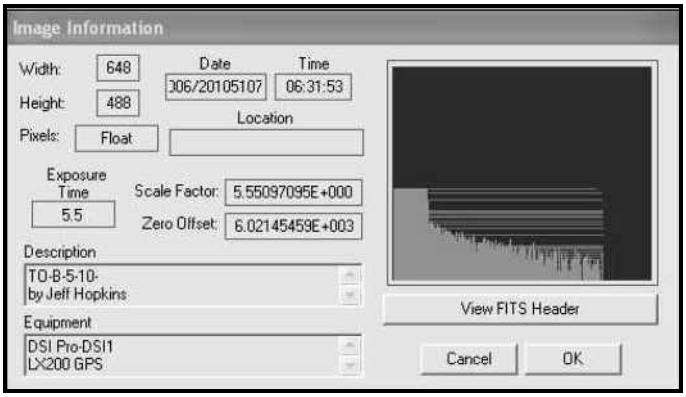

Figure G–1. Image Information.

Header Details

From the **Autostar Image Processing** menu, at the lower right of the **Image Information** window, select **View FITS Header** to see the information for the selected .fts image. (Fig. G-2.)

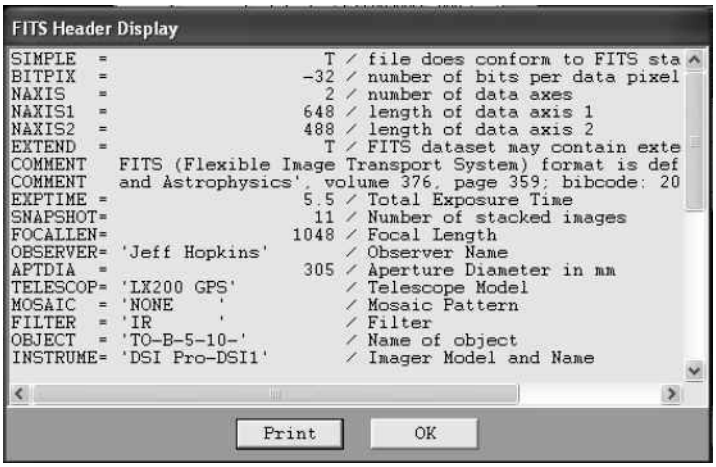
FITS Header Display
SIMPLE = T / file does conform to FITS sta
BITPIX = -32 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 648 / length of data axis 1
NAXIS2 = 488 / length of data axis 2
EXTEND = T / FITS dataset may contain exte
COMMENT FITS (Flexible Image Transport System) format is def
COMMENT and Astrophysics', volume 376, page 359; bibcode: 20
EXPTIME = 5.5 / Total Exposure Time
SNAPSHOT= 11 / Number of stacked images
FOCALLEN= 1048 / Focal Length
OBSERVER= 'Jeff Hopkins' / Observer Name
APTDIA = 305 / Aperture Diameter in mm
TELESCOP= 'LX200 GPS' / Telescope Model
MOSAIC = 'NONE ' / Mosaic Pattern
FILTER = 'IR ' / Filter
OBJECT = 'TO-B-5-10-' / Name of object
INSTRUME= 'DSI Pro-DSI1' / Imager Model and Name
Print
OK

Figure G–2. FITS Header.

APPENDIX H
Lightbox Design and Construction

This section briefly discusses the need for flat fields, alternate methods of imaging flat fields, and the design and construction of a light box.

Flat Fields

The purpose of taking images of a uniformly illuminated field is to permit calibration of the photometry images, by eliminating artifacts due to uneven response across the CCD chip, pixel defects, and shadows caused by out–of–focus dust particles and other debris ("dust doughnuts") in the optical train. Examination of an image taken of an evenly–illuminated field readily shows up these inevitable problems. The so–called "flat field image(s) are algebraically subtracted from the data images during calibration through the software. The technical challenge is in achieving a uniformly illuminated field, and a proper exposure. The exposure issues are discussed elsewhere.

There are several methods used in obtaining flat fields, in increasing order of uniformity and consistency:

(4) Sky Flats – Flat Field images may be made during twilight, as the sky either grows darker or lighter. Difficulties to be overcome include gradients in sky brightness, presence of star images, and the short time period during which the sky illumination is useful, and remains relatively constant.

(3) Dome Flats – Images may be taken of a suitably placed flat white surface, illuminated indirectly. This is frequently used by professionals with large telescopes, enclosed in a dome (or other enclosure). A flat panel is mounted on the inside of the dome. A white panel could be used for portable use, provided the illumination is even, and directed from the side. Care must be taken not to allow extraneous light to enter the telescope directly.

(2) "Tee Shirt" Flats – A variant technique employing a white cloth stretched over the front of the telescope, to diffuse the light source. As with dome flats, the light source must not be allowed to shine directly into the telescope. A second stretched cloth diffuser might also be placed over the light source. One advantage is the method may be used during daytime, provided that no light is allowed directly into the optical train.

(1) Light Box Flats – This is probably the best and most consistent method. A lightweight box or enclosure is fabricated and placed over the entrance to the telescope optics. The box typically contains one or more diffuser sheets, and small lamps or light–emitting diodes (LEDs) which are arranged to shine upward onto the inside of the box, which is constructed of white diffusing material. If used outdoors with other observers and telescopes in the vicinity, the box should be sealed against possible light leaks.

Light Box Construction Notes

At HPO, we researched a dozen or more web pages detailing construction of light boxes, including several offering commercial products for sale. The consensus on size, construction materials, and suggested light sources was as follows:

Box Size – Up to about a 12 inch (30 cm) telescope aperture, the preferred box size was approximately 14 inches (35.6 cm) square, with the length about the same or a little shorter. In other words, a cube. a little larger than the maximum telescope tube end size (or corrector cell OD on SCTs). The box size could be reduced for telescopes 8 inches (20cm) or smaller, and an even smaller size could be made for telephoto lenses.

Construction Material – The preferred material seems to be “Foamcore” sheeting, which is a styrene plastic foam sheet (the core) covered in white matte paper. It is stiff and lightweight, typically 1/4 inch (6 mm) thick, and readily available in 30 x 40 inch (.75 x 1 m) (and larger) sheets in arts and craft supply stores. It is inexpensive, easily cut to size, and also comes in black.

The joints may be attached together using a hot glue gun, or tape (fabric duct tape or packing tape). RTV or silicon adhesive (bathtub caulk) could be used, but the advantage of hot glue is that it dries rapidly, thus the panels don't need to be supported in position for very long. Some attention should be paid to access to the interior, for adjustment of the lights or cleaning. Perhaps a side panel or the top should be arranged for easy removal.

A layout should be planned for sheet cutting. A few web pages discussed round or tubular designs; some were constructed in sheet metal; and one web page described a box made of thin plywood (door skin material comes to mind); but that would need to be either lined in white material or painted to be reflective inside, and would necessarily be heavier.

Attachment – To attach the lightweight box to the end of the telescope, a soft plastic foam ring or collar is usually shaped or cut, to fit around the end of the tube, and placed inside the end of the box. But construction grade Styrofoam "bead board" is to be avoided, as it tends to shed particles which will stick by static electricity to the diffuser panel inside the box. Flexible polyethylene foam blocks or sheets used in packing material may be readily salvaged and put to use. Sometimes large thick sheets can be obtained, from which a complete ring or collar can be cut.

Diffuser Panels – Most light box designs employ one or two diffuser panels mounted across a ring or bulkhead with an opening of at least the full size of the telescope aperture, cut from the same foamcore material as the walls of the box. Frosted translucent drafting mylar sheet or vellum is usually recommended, although this material is rapidly becoming difficult to obtain, as draftings are now created and stored electronically. Thin milk–white opaque plastic sheet may be obtained from sign shops or plastics dealers. But the thickness must be selected so as to pass adequate light.

Light Sources – Small incandescent battery–operated lamps or LEDs are typically preferred, although some heavy–duty designs for larger telescopes in observatories have employed AC lamps and/or fluorescent tubes.

Wiring and Electrical Supply – Batteries or low–voltage AC transformer adapters may be used, with the lamps or LEDs wired either in series or parallel. Some designs feature adjustable voltage to control the illumination. Some designs have experimented with both incandescent lamps and LEDs, selectable with switches. Flashlight bulbs do not seem to be very useful, as the molded bulbs project disturbing dark and light patterns. LEDs present several concerns: they may only be adjusted through a short range with a conventional potentiometer (voltage adjustment) circuit; a series resistor must be employed, to limit the current; and the proper polarity of the DC voltage must be observed.

The color temperature of the lamps or LEDs (typically the bright white type) has been discussed in detail by some workers, but this is less of a factor in photometry, as the exposure is adjusted separately for each filter. A simple battery box with an On–Off switch can be constructed, and attached to the outside of the box with hook–and–loop fasteners. The switch may even be dispensed with, and the battery or power supply simply disconnected when not in use.

Light Arrangement – The lights are carefully arranged to shine upward against the inside of the top of the box, so that the light is evenly diffused. It is important that the lights not be permitted to shine directly into the diffuser panel(s). Some constructions use small baffles, made of the same foamcore material as the box and light mountings, typically placed in the corners of the box. A small piece of translucent frosted material, perhaps mylar tape, placed over the individual bulbs or LEDs may help to soften and diffuse the light pattern.

Plans and Further Details

Details of light box construction are shown in the photographs following, and a suggested layout plan may be seen on the HPO web pages. (URL: http://www.hposoft.com/Astro/astro.html) A web search on "CCD light box flats" will yield a number of examples of light boxes successfully used in CCD imaging that will be useful for photometry. The details of setting exposures in each filter band, imaging flats, and using the flat field files for calibration are given in other sections of this book.

HPO Light Box

The following photographs and description illustrates the construction of a flat field light box in use at the Hopkins Phoenix Observatory (HPO), installed on a 12 inch (30.5 cm) aperture Meade LX200 GPS telescope.

Construction material was ordinary thick cardboard, cut and taped into a simple box painted white on the inside to reflect and diffuse the light, and black on the outside, to waterproof it against dew. (Fig. H-1.)

Figure H-1. Interior Construction of HPO Light Box.

Joins in the cardboard material have not given any problem in the flat field images. The box is just large enough in width to accommodate the 13.25 inch (33.65 cm) outside diameter front cell of the LX200 telescope corrector lens. The inside length is approximately the same as the width (a cube). Three small spring wire feet slide into the cell to hold the light box in place when taking flat field exposures. The telescope is pointed straight upward with the light box attached during flat field imaging, typically conducted at the conclusion of each night's imaging session.

A 1/4 inch (6.5 mm) thick plywood bulkhead is installed slightly inside the open end of the white-painted box, which rests upon the end of the telescope corrector cell when in use. (Fig. H-2.) The plywood bulkhead is secured in place with self-tapping screws through the sides of the box. A 12 inch (30.5 cm) diameter hole in the bulkhead lets the light into the telescope aperture. On the inside of the bulkhead, white paper covers the hole, serving as a light diffuser.

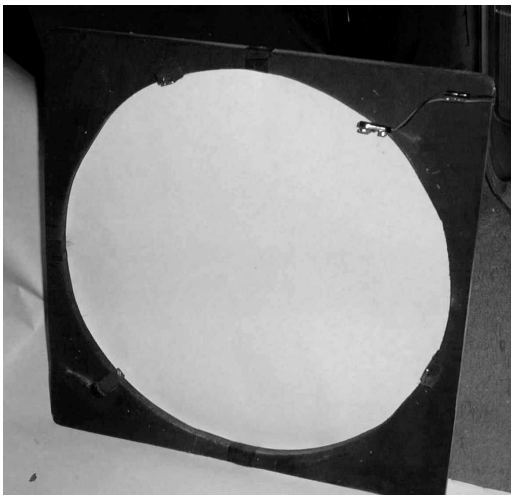

Figure H-2. Outside of Plywood Bulkhead with Aperture. (This Side Goes Against the Corrector Cell).

Attached on the inside corners of the bulkhead are four small incandescent lamps with attached power wires. (Fig. H-3.) Small pieces of white paper in the corners serve to block the light from impinging directly upon the diffuser sheet, and help direct the light upward, inside the box. The wiring for the four lamps is soldered together and connected to a 9VDC battery, which is simply hung on the outside of the box, and unplugged when not in use. No voltage regulation is used.

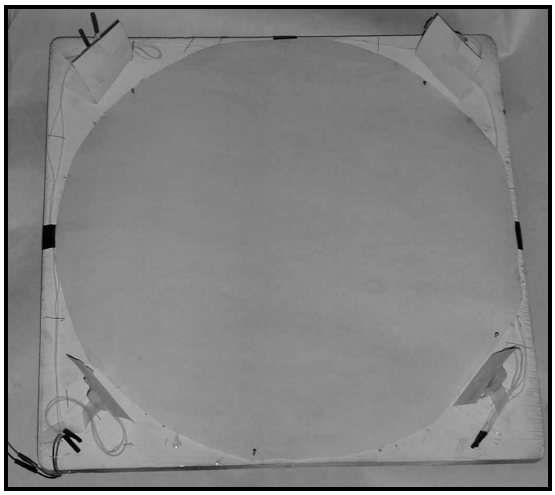

Figure H-3. Inside of Plywood Bulkhead. Wired Lamps Are Mounted in Four Corners, with Light Baffles.

Flats taken with the light box have shown to be more consistent than other methods, including "sky" flats taken during twilight. (See Figures H-4 and H-5.) While these two flats look very different, that is because of the contrast settings. Both flat field images are actually very close, and work fine.

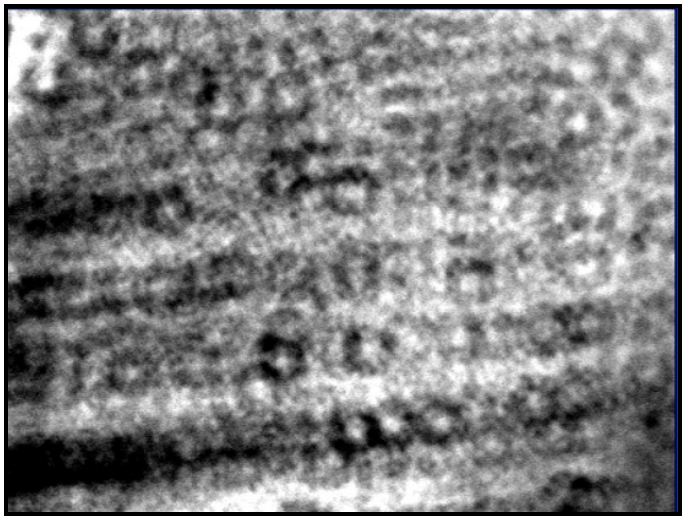

Figure H-4. Typical Light Box Flat Field (V Filter), Showing Artifacts Due to Dust Particles on the Optical Train.

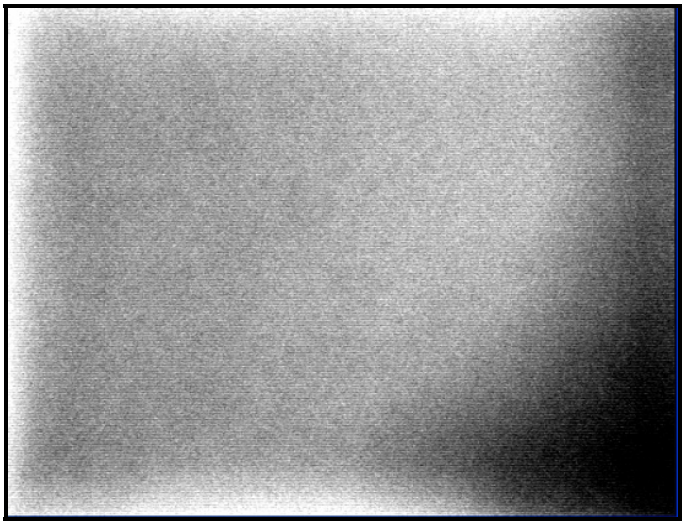

Figure H-5. Typical Twilight Sky Flat, Showing Mostly Uneven Illumination, But Some Artifacts Are Also Present.

APPENDIX I
Suggested Projects

Introduction

There are many types of astronomical photoelectric photometry projects. Some of the projects an amateur might consider are Lunar photometry, solar photometry, planetary photometry, planetary satellite occultation photometry, asteroid photometry, comet photometry, deep sky photometry (including Novae, Supernovae, and galactic photometry), and several varieties of stellar photometry.

Lunar Photometry

Lunar photometry is an area in which few astronomers are performing photometric observations. Lunar photometry of **transient events** such as the brightening or fading of certain areas and discolorations of the crater floors can be done.

Perhaps one of the most interesting types of Lunar photometry is the measurement of **lunar occultations** of stars. The darkened limb of the moon provides a "knife edge", rapidly cutting off the star light. Much can be learned from the data obtained. High–speed photometry is used and data points may be logged into a computer at 1-millisecond intervals. The resulting light curve and diffraction pattern of the light from the star as it is sliced by the darkened edge of the moon can reveal unseen multiple stars (such as previously undetected spectroscopic binaries) and information about their configurations. This is a very exciting project because you only get one chance and everything must be just right. These measurements can be made with either a waxing or waning moon. Measurements can be made from stars disappearing or re–appearing on the darkened Lunar limb. Unless you have an exceptionally fine telescope setup and very accurate clock drive, projects involving the disappearance of a star are the best ones to tackle.

Lists of the brighter lunar occultations occurring during the year are published in ***SKY and TELESCOPE*** magazine and the ***RASC Observers Handbook***. The **International Occultation Timing Association (IOTA)** is another good source of information about upcoming events and techniques. (See the **References** section of this book for more information.)

Solar Photometry

Solar photometry offers some unique challenges. Certainly only a small telescope is needed. The problem with solar photometry is just the reverse of other photometry – It's TOO bright! Because the Sun is the nearest star and we are totally dependent on it, its study is of great importance. Areas that can be investigated include the sunspots and the quiet (no sunspot activity) Sun's limb darkening.

CAUTION: Special filters and other precautions are needed, due to the overwhelming intensity of the Sun!

Planetary Photometry

There has been a growing interest in planetary photometry. By observing the light changes as a function of the solar phase angle, information about the object's surface composition can be obtained. There has also been recent interest in photometry of the Galilean satellites of Jupiter and work is being done on Saturn's satellites.

Planetary Satellite Photometry

Photometry of **planetary occultations** and **satellite transits** is another project suitable for the smaller observatory. Doing photometry of Pluto and Charon as they occult each other has been a recently organized project. Recent data published that used UBV photometry was able to reveal the different colors of Pluto and Charon as they occulted each other.

Comet Photometry

With each appearance of a new comet, interest in comet photometry is revived. This is a very specialized form of photometry, and **special filters** are usually needed to acquire data on the gaseous emissions. The photometrist with a UBV or BVRI photometer can still make valuable observations, however.

Before getting too far into comet photometry, it is advisable to contact some of the comet photometry experts. (See the **References** section.) Also, keep an eye out for any new comets. You may be the first to do photometry on them.

Stellar Photometry

Stellar photometry is probably the most popular and useful project undertaken by amateur astronomers. A great many stars have light that is not constant. These form the class known as variable stars. Projects ranging from just timing of eclipses to detailed filter photometry are well within the capability of the amateur astronomer with modest equipment.

The variable light output from stars can be caused by several phenomena. Basically, there are three types of variable stars: **intrinsic variables**, **eruptive variable**s, and **extrinsic variables**. With some variable star projects, only timing of the period of the cyclic variation in white light is important. Others require filter photometry and careful calibration of the system and comparison stars. The following is a list of characteristics of the different types of variable stars:

Intrinsic Variables

The intrinsic variables exhibit light variations caused by internal phenomena. The star may pulsate (e.g., **Cepheid** variables). This pulsation may be of a long period (**Miras**) or a short-period pulsation, semi–regular, or irregular. Also, a relatively new group of stars, known as **RS CVn** variables are believed to have large star spots (similar to sun spots only much larger) that travel around on the surface of the star. These spots are cooler than the rest of the surface, so as they migrate they cause the star's brightness to change.

Eruptive Variables

The eruptive variables tend to produce sudden, unpredictable outbursts of energy. Examples are Flare stars (**Cataclysmic Variables**), Novae, and Supernova types. Amateurs have done yeoman duty in coordinating ground-based observations with professionals, as sort of an "early warning" network to help schedule space satellite observatories.

Extrinsic Variables

These stars exhibit light variations caused by external reasons, e.g., such as another object (a star, an extrasolar planet, or a protoplanetary disk) passing in front of them. These are typically noted as eclipsing binaries. But while they may be studied as **eclipsing binary stars**, the systems may actually contain more than two stars and may also have intrinsic and eruptive variables within the system. Using standard UBVRI photometric filters, additional information can be obtained. **HPO** is monitoring **Epsilon Aurigae**, an interesting eclipsing star with a very long (27.1 years) period.

Nova and Supernova Photometry

While photometric studies of Novae (in our own galaxy) and Supernovae (SNe) are certainly important, it is rare that amateurs have the opportunity to follow them. Faint SNe occur frequently in other galaxies, but detecting them is usually beyond the means of most amateurs. Photometry of active Seyfert galaxies may be within the limits of amateur equipment.

Asteroid Photometry

Asteroid photometry is challenging, as they are usually fast moving and relatively faint, but white light curves can be acquired without specialized filters. Asteroid light curves are of strong interest, as rotation rates, sizes, and surface colors (compositions) can be investigated. The light curves also aid in modeling radar observations to map the shapes. Amateurs can perform important work by quickly responding with observations of fast-moving Earth-crossing objects. Information can be obtained to confirm the size and trajectory of potentially hazardous asteroids. Some of these are being confirmed as binary objects, some with satellites.

APPENDIX J
References

Reference

Miles, R., "UBVRI photometry using CCD cameras," JBAA **108** 2, 1998, pp. 65-74. (Reference magnitudes and finding charts for M67.)

Books and Software

Beginning to Intermediate Level

Note: The following books and software listed are available from Willmann-Bell, Inc. URL: http://www.willbell.com.

Astronomical Photometry - Arne Henden and Ron Kaitchuck. A classic, comprehensive text. (Recently out of print.)

CCD Astronomy, Construction and Use of an Astronomical CCD Camera, - C. Buil, 1991.

AIP4WIN - Astronomical Image Processing for Windows. Version 2, 2007. Richard Berry and Jim Burnell. Comprehensive text book and CD-ROM software for CCD image processing, including photometry and astrometry. Full tutorials and sample images on disk.

Solar System Photometry Workbook. R. Genet, 1983.

USNO-MICA - U.S. Naval Observatory Multiyear Inter-active Computer Almanac (MICA) 1800 - 2050 software.

Current College-Level Textbooks

Introduction to Astronomical Photometry Using CCDs.
Dr. Bill Romanishin, Oklahoma U. (167 pgs, PDF)
http://www.observatory.ou.edu/book2513.html
On-line textbook, classroom notes.

Introduction To Astronomical Photometry, Edwin Budding**,** Cambridge U. Press, 2007.

Handbook of CCD Astronomy (2nd Ed.) -- Steve B. Howell, Cambridge U. Press, 2000.

Web Resources

AAVSO Julian Day Calculator - On-line JD conversion.
http://www.aavso.org/observing/aids/jdcalendar.shtml

Eclipsing Binary Star Predictions - On-line elements generator.
(J.M. Kreiner, 2004, Acta Astronomica, **54**, 207-210)
http://www.as.ap.krakow.pl/ephem/ORI.HTM

SIMBAD - On-line astrophysical object reference data source.
http://simbad.u-strasbg.fr/simbad/

Smithsonian/NASA-ADS Astrophysical Data Service -
On-line library of abstracts and scanned journal articles.
http://adsabs.harvard.edu/bib_abs.html

Organizations

AAVSO - American Association of Variable Star Observers
http://www.aavso.org
On-line variable star charts, observing programs and aids, JD calculator, CCD manuals, Journal. Data base of light curves and data archiving.

ALPO - Association of Lunar and Planetary Observers
http://www.lpl.arizona.edu/alpo
Solar system observing programs. Lunar transients/impacts observing programs.

BAA-VSS - British Astronomical Association - Variable Star Section. http://www.britastro.org/vss
Variable star observing programs.

CBA - Center for Backyard Astronomy -
http://cba.phys.columbia.edu
Cooperative worldwide network of observers for cataclysmic variable stars, headed by Dr. Joe Patterson at Columbia U. NYC.

HPO - Hopkins Phoenix Observatory - Epsilon Aurigae 2009 Campaign
http://www.HPOSoft.com/Astro/astro.html
Newsletter and coordination of observations of Epsilon Aurigae during upcoming 2009-11 eclipse season, headed by Dr. Robert Stencel, U. of Denver and Jeff Hopkins, Hopkins Phoenix Observatory.

IOTA - International Occultation Timing Association
http://www.occultations.org
On-line lunar and asteroid occultation predictions, maps, expedition/observing coordination. Has separate European Section (IOTA-ES).

IAU-MPC - International Astronomical Union Minor Planets Center. http://cfa-www.harvard.edu/iau/mpc.html
Official reporting center for asteroid discovery observations and announcements, database, statistics, Minor Planet Circulars.

Meade 4M Community
http://www.meade4m.com
News about Meade products. Software updates and downloads.

MPML - Minor Planets Mailing List
http://tech.groups.yahoo.com/group/mpml
E-mail discussion list for asteroid and comet observers. New objects announcements, coordination of light curve photometry with radar observations.

MPO - Minor Planet Observer
http://www.MinorPlanetObserver.com
Journal and collaborative asteroid observing programs, coordinated by Brian Warner. Canopus photometry software, and Collaborative Asteroid Light Curve (CALL) program.

RASC - Royal Astronomical Society of Canada -
http://www.rasc.ca
Publishers of annual *Observers Handbook* with occultation predictions. Variable star section observing programs, charts.

RASNZ-VSS - Royal Astronomical Society of New Zealand - Variable Star Section. http://www.rasnz.org.nz/vss/vss.html
Active coordination of variable star observations in southern hemisphere.

SAS - Society for Astronomical Sciences.
http:www.socastrosci.org
Sponsor of annual amateur-professional conference held in Big Bear Lake, California.

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